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High subsidence vulnerability in Denpasar's coastal wetlands: Geotechnical characterisation of soft soils and implications for sustainable zoning

I Gusti Ngurah Putu Dharmayasa[1*], I Putu Sugiana[2], Roberth Evander Meidudga[3]

[1] Department of Civil Engineering, Faculty of Engineering and Informatics, Universitas Pendidikan Nasional, Denpasar 80224, Indonesia
[2] Department of Aquatic Resources Management, Faculty of Agriculture, Science and Technology, Universitas Warmadewa, Denpasar 80235, Bali, Indonesia
[3] Department of Civil and Structural Engineering, University of Sheffield, Mappin Street, Sheffield, United Kingdom
* Corresponding author's e-mail: ngurahdharmayasa@undiknas.ac.id

ABSTRACT

Rapid urbanisation in the coastal wetlands of Denpasar, Bali, is intensifying pressure on soft, highly compressible soils and increasing the risk of land subsidence. Yet, geotechnical evidence directly linked to coastal planning decisions in this area remains limited. This study aims to characterise the physical properties of coastal wet soils and assess their subsidence vulnerability to support sustainable coastal planning in Denpasar. Surface soils were sampled at 50 cm depth from five representative land-use types: agricultural land, marshland, Mudflat, abandoned aquaculture ponds, and mangrove areas. Fifteen undisturbed samples were analysed for water content, bulk and dry unit weight, and grain-size distribution following national SNI standards. Fine fractions were further examined using hydrometer tests and classified according to the Unified Soil Classification System (USCS), while the relationship between water content and dry unit weight was evaluated using Pearson's correlation. Supplementary Cone Penetration Test (CPT) data from adjacent sites were used to place the shallow measurements in a broader subsurface context. The results show a strong inverse relationship between water content and dry unit weight, silt-dominated SM and SP–SM textures across sites, and CPT evidence of a thick, highly compressible soft layer, collectively indicating high subsidence susceptibility. These findings demonstrate that mangrove and marshland zones are intrinsically unsuitable for conventional development, whereas abandoned aquaculture areas are more favourable for development under proper geotechnical management. Overall, the study provides a site-specific geotechnical baseline that can be directly translated into zoning, risk mapping, and foundation-planning strategies for resilient coastal development in Denpasar.

Keywords: coastal soft soils, land subsidence vulnerability, soil physical properties, sustainable coastal planning, grain-size distribution.

INTRODUCTION

The development of Denpasar City, the capital of Bali Province, has progressed rapidly, with nearly all areas of the city, including its coastal zones, now built up. The coastal areas of Denpasar are under increasing development pressure from residential expansion, agriculture, and other economic activities. For instance, Denpasar City loses approximately 0.145 km² of agricultural land each year (Rahmadani et al., 2024), while mangrove cover declined by 0.26 km² for the period 2006–2020 (Rejeki et al., 2023). In the face of such development pressures, a comprehensive understanding of the soil characteristics in this region is essential for sustainable land-use planning and for mitigating the risk of land subsidence (Ewunetu et al., 2025).

Wetlands in coastal areas, particularly those composed of soft soils, possess unique physical properties and are highly sensitive to loading changes (Liu and Jiang, 2020). The key characteristics of such soft soils include very high-water content, high compressibility, low shear strength, and a soft consistency (Sun et al., 2021). These properties make the soil prone to significant and prolonged compression (consolidation) when subjected to loading—whether from heavy infrastructure development such as multi-story buildings, or from excessive groundwater extraction, which reduces pore water pressure and triggers ground subsidence (Nguyen, 2024; Zhou et al., 2025).

Concrete evidence of this phenomenon can be clearly observable in various coastal regions of Indonesia. In Jakarta, the combination of massive urban development and intensive groundwater extraction has led to land subsidence exceeding 20 cm per year in some areas, resulting in severe tidal flooding and extensive infrastructure damage (Abidin et al., 2011; Hendarto et al., 2011; Sidiq et al., 2025). Similarly, the city of Semarang faces serious challenges, with an average land subsidence rate of 10–12 cm per year, driven by excessive groundwater use and rapid urban expansion (Abidin et al., 2013). On a global scale, the city of Tokyo, Japan, once experienced land subsidence of up to 10 cm per year, with a maximum rate reaching 24 cm per year in 1968 before groundwater regulations were implemented (Sato et al., 2006). Other countries have faced similar issues – for instance, Shanghai, China, recorded subsidence rates of up to 2.42 cm per year (Wang et al., 2012), with cumulative subsidence reaching 2–3 m by 2004 (Chai et al., 2004). Likewise, Bangkok, Thailand, experienced an average land subsidence rate of about 2 cm per year between 1983 and 2011 (Aobpaet et al., 2013), while New Orleans, United States, has also undergone ground subsidence primarily due to peat soil compaction (van Asselen et al., 2024). Such subsidence poses a serious threat to urban sustainability and heightens vulnerability to flooding and sea-level rise. These cases highlight that, absent careful management and a deep understanding of soft soil characteristics, coastal development can inadvertently trigger disasters that undermine the region's sustainability (Erkens et al., 2015; Sarah, 2022).

While global evidence suggests that soft soils are highly prone to compression and subsidence, a localised, data-driven assessment linking soil physical characteristics directly to zoning decisions and coastal planning frameworks in Denpasar remains lacking. Coastal cities increasingly rely on geotechnical indicators – such as water content, unit weight, and grain-size distribution – to guide land-use suitability, drainage design, and environmental protection measures. Integrating soil vulnerability parameters into spatial planning decisions is therefore essential to prevent long-term settlement, reduce infrastructure failure, and support climate-resilient development (Youssef et al., 2021; Cao et al., 2024).

This study aims to analyse the physical properties of wetland soils in the coastal area of Denpasar based on laboratory test data, focusing on parameters such as water content, unit weight (wet and dry), and grain size distribution. By understanding the variations in soil characteristics across different land-use types, this research seeks to provide valuable insights to support informed decision-making in coastal development and conservation efforts.

In the context of sustainable development, understanding soil characteristics in coastal areas is essential not only for construction-related technical purposes but also as a foundation for environmentally conscious urban planning. Wetlands function as natural carbon sinks and vital water filtration systems. Thus, characterising soil physical properties is a key scientific step in identifying areas suitable, conditionally suitable, or unsuitable for development. The integration of soil-based subsidence vulnerability indicators into planning instruments ensures that future development in Denpasar aligns with the principles of resilient and sustainable coastal management.

METHOD

Research location

This research focuses on the southern or coastal area of Denpasar City, a region characterised by intense human activity and long-standing land-use transformations. The area presents a compelling case for study due to the diverse pressures placed on wetland ecosystems, reflecting critical forms of human intervention within the study region. Such interventions include the Suwung landfill site, which poses challenges related to soil stability and potential leachate contamination (Arbain et al., 2012; Anny et al., 2025). Similarly, Serangan Island has undergone extensive environmental engineering to support its development as a major tourism destination, which has indirectly increased loading on the underlying soil and altered the local hydrological patterns (Darmawan et al., 2018).

In addition, the widespread conversion of wetlands for residential and housing development has become a dominant activity that accelerates soil consolidation processes and may potentially trigger land subsidence (Sunarta et al., 2022). A clear spatial representation of the distribution of observation points and the specific locations of soil sampling across the wetland areas in southern Denpasar is presented in Figure 1.

Data collection and analysis

To conduct this research, the initial stage involved collecting primary data through soil sampling at the research sites using a hand auger. Soil samples were collected at three sampling points per location (representing different land-use categories), each at a depth of 50 cm. The land-use categories where soil samples were collected include agricultural land (SW1, SW2, SW3), marshland (ML1, ML2, ML3), mudflat (MF1, MF2, MF3), abandoned aquaculture ponds (TB1, TB2, TB3), and mangrove areas (DM1, DM2, DM3). The collected soil samples were subsequently analysed in the laboratory, including tests for water content, bulk density, and grain size distribution.

A total of 15 soil samples (N=15) were collected for laboratory analysis, representing three sampling points across each of the five land-use categories. Statistical analysis, particularly the relationship between water content and dry unit weight, was evaluated using the Pearson Correlation Coefficient to quantify the strength and direction of the linear association. The five distinct land-use categories – agricultural land, marshland, Mudflat, abandoned aquaculture ponds, and mangrove areas – were strategically selected based on their representative status of the dominant human intervention and natural wetland types in Denpasar's coastal zone. This selection strategy provides a comprehensive comparative basis for assessing subsidence vulnerability: Mangrove and Marshland represent the natural, highly susceptible state of soft coastal deposits; Agricultural Land and Abandoned Aquaculture Ponds capture the effects of varying degrees of past human modification and potential compaction; and the Mudflat represents a crucial transitional intertidal environment. By comparing geotechnical characteristics across these representative zones, the study effectively distinguishes the impact of specific land uses on soil properties and establishes a nuanced, site-specific risk assessment for coastal planning.

The water content test was conducted in accordance with SNI 1965:2008 – Method for Determining Water Content of Soil and Rock in the Laboratory (BSN, 2008). The purpose of this test is to measure the percentage of water contained in the soil relative to its dry weight. The soil water content was calculated using Equation 1.

$$W_c = \left(\frac{M_w - M_d}{M_d}\right) \times 100\% \quad (1)$$

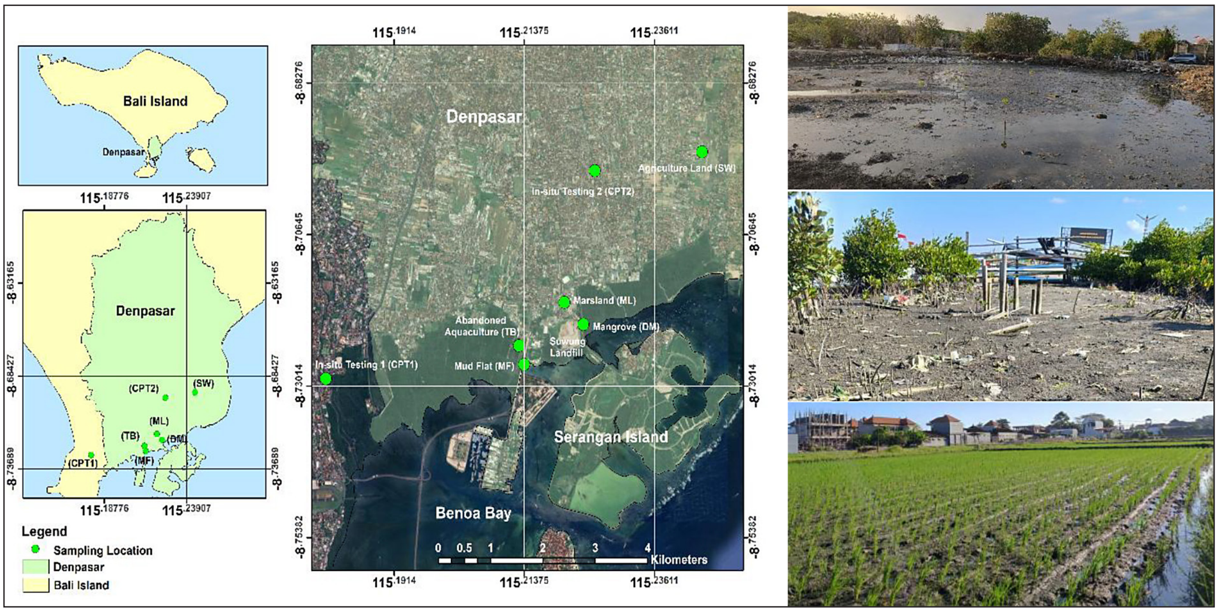

Figure 1. Research location and the field condition soil sampling points

where: W_c represents the water content (%), M_w is the weight of the wet soil (g), and M_d is the weight of the dry soil (g).

The bulk density test (γ) was conducted in accordance with SNI 03-3637-1994 – Method for Testing the Bulk Density of Fine-Grained Soils Using a Mold Specimen (BSN, 1994). The purpose of this test is to measure the weight per unit volume of soil in both wet (γ_b) and dry (γ_d) conditions. The bulk unit weight is the total weight of soil (solid particles and water) per unit volume and is calculated using Equation 2.

$$\gamma_b = \frac{W_{total}}{V_{total}} = \frac{(W_{solid} + W_{water})}{V_{total}} \tag{2}$$

where: γ_b is the bulk unit weight (g/cm³), W_{total} is the total weight of the soil sample (g), and V_{total} is the total volume of the soil sample (cm³).

The dry unit weight represents the weight of the solid particles only, per unit of total volume. It serves as an important indicator of soil compaction, particularly for field compaction control. The dry unit weight is calculated using Equation 3.

$$\gamma_d = \frac{W_{solid}}{V_{total}} \tag{3}$$

where: γ_d is the dry unit weight (g/cm³), W_{solid} is the weight of the solid soil particles (g), and V_{total} is the total volume of the soil sample (cm³).

The sieve and hydrometer tests were conducted in accordance with SNI 3423:2008 – Method for Soil Particle Size Analysis (BSN, 2008). The purpose of these tests is to determine the grain size distribution and the percentage of silt and clay fractions. The sieve analysis employed sieves with mesh numbers 4 (4.75 mm), 10 (2.00 mm), 16 (1.10 mm), 30 (0.60 mm), 40 (0.43 mm), 60 (0.25 mm), 100 (0.15 mm), and 200 (0.08 mm). Soil classification was carried out using the Unified Soil Classification System (USCS) based on the particle size composition. The soil sampling procedure and laboratory testing process are illustrated in Figure 2.

To provide regional context for the subsurface stratigraphy and the extent of the soft soil formation, supplementary geotechnical data from two

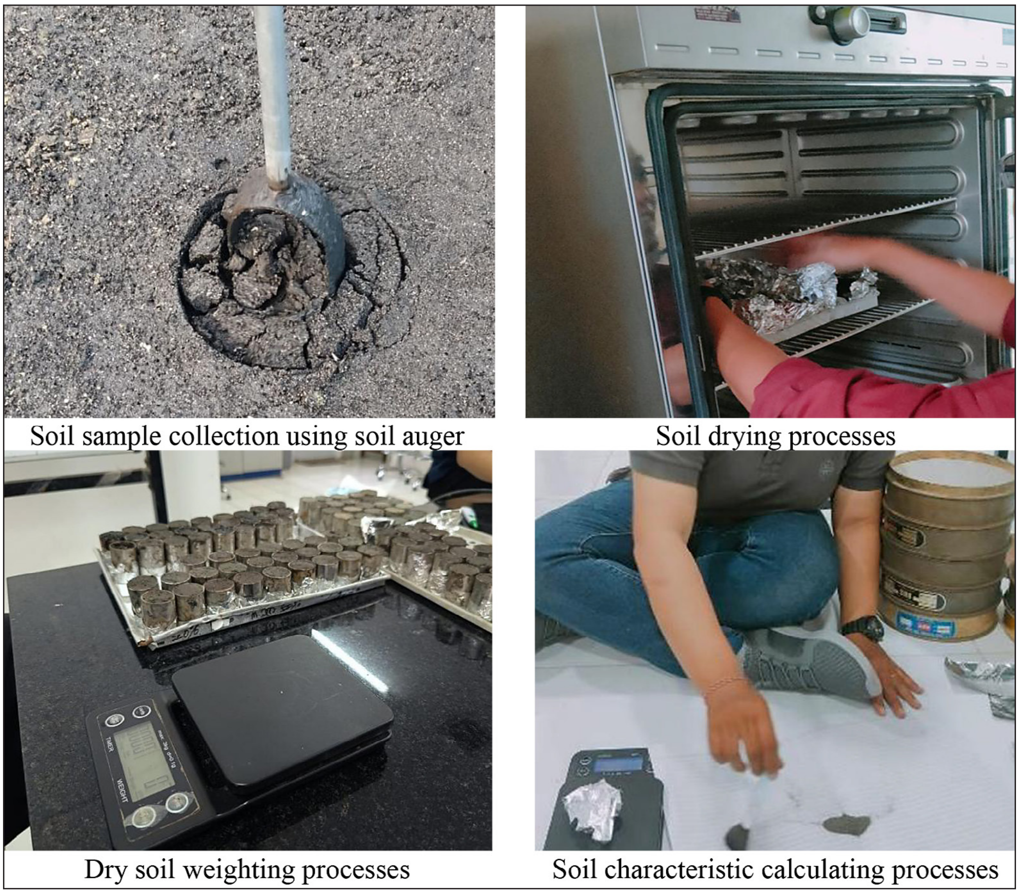

Figure 2. Documentation of laboratory analysis processes

nearby locations were utilised. Table 1 presents the Cone Penetration Test (CPT) results (CPT 1 and CPT 2), showing cone resistance (qc) at various depths. This data confirmed the presence of a thick, highly compressible soft soil layer in the region, extending to depths of up to based on low cone resistance values.

The CPT results presented in Table 1 serve as critical supplementary data. Low cone resistance values (q_c), particularly readings consistently below 1–6 m (CPT 1) and intermittent low values extending up to (CPT 2, Point 2), confirm the regional presence of thick, highly compressible soft soil layers. This subsurface profile validates the study's focus on land subsidence vulnerability, demonstrating that the critical compression layers extend far beyond the shallow sampling depth and provide the geotechnical context for the poor index properties observed in the laboratory samples.

RESULTS AND DISCUSSION

Water content characteristics

Water content varies significantly across locations, with the highest value recorded in the mangrove area at 67.36%, followed by marshland at 50.15%, agricultural land at 41.58%, Mudflat at 34.84%, and the lowest in the abandoned aquaculture at 25.77% (Figure 3). The relatively high water content in the mangrove zone indicates a highly saturated condition, with most soil pores filled with water. Such saturation has implications for high consolidation and compressibility potential when the soil is subjected to loading (Alnmr et al., 2024).

Water content also reflects soil characteristics and behaviour, particularly in relation to particle size. Fine-grained soils (such as clay) have a greater capacity to retain water compared to coarse-grained soils (such as sand). This is due to the much larger specific surface area and smaller pore spaces in clay soils, whereas coarse-grained soils like sand have larger pores that allow water to drain more easily (Al Majou et al., 2022).

Bulk and dry unit weight

The highest density was found in the abandoned aquaculture area (TB), with an average bulk unit weight (γ_b) of 1.96 g/cm³ and an average dry unit weight (γ_d) of 1.40 g/cm³ (Figure 4; Table 2). This condition indicates a relatively dense soil composition with a high proportion of solid materials.

In contrast, the mangrove area (DM) exhibited the lowest density, with an average bulk unit weight (γ_b) of 1.45 g/cm³ and an average dry unit weight (γ_d) of 0.69 g/cm³. The lowest dry bulk density (γ_d) was recorded at the mangrove site (DM 1) with a value of 0.483 g/cm³, followed by the marshland site (ML 1) at 0.743 g/cm³. These low values reflect very soft soils dominated by organic matter and water, indicating high porosity

Table 1. Supplementary CPT results showing cone resistance (q_c) across different depths in adjacent coastal areas

Depth (m)	CPT1			CPT2	
	Cone resistance (kg/cm²)			Cone resistance (kg/cm²)	
	Point 1	Point 2	Point 3	Point 1	Point 2
0	0	0	0	0	0
1	15	5	10	32	30
2	5	5	5	20	15
3	5	5	5	50	50
4	5	5	20	25	20
5	50	20	20	15	10
6	10	5	5	22	5
7	80	110	140	15	20
8	250	250	250	15	20
9	250	250	250	80	10
10	250	250	250	10	30
11	250	250	250	200	50
12	250	250	250	200	15

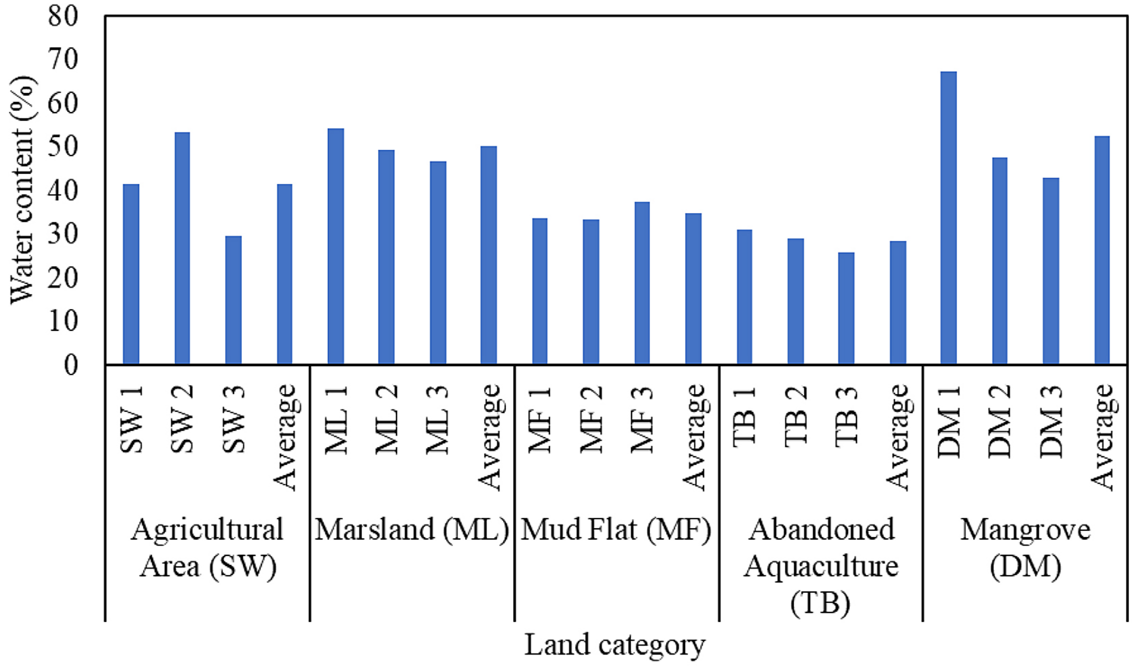

Figure 3. Summary of water content for each sampling point

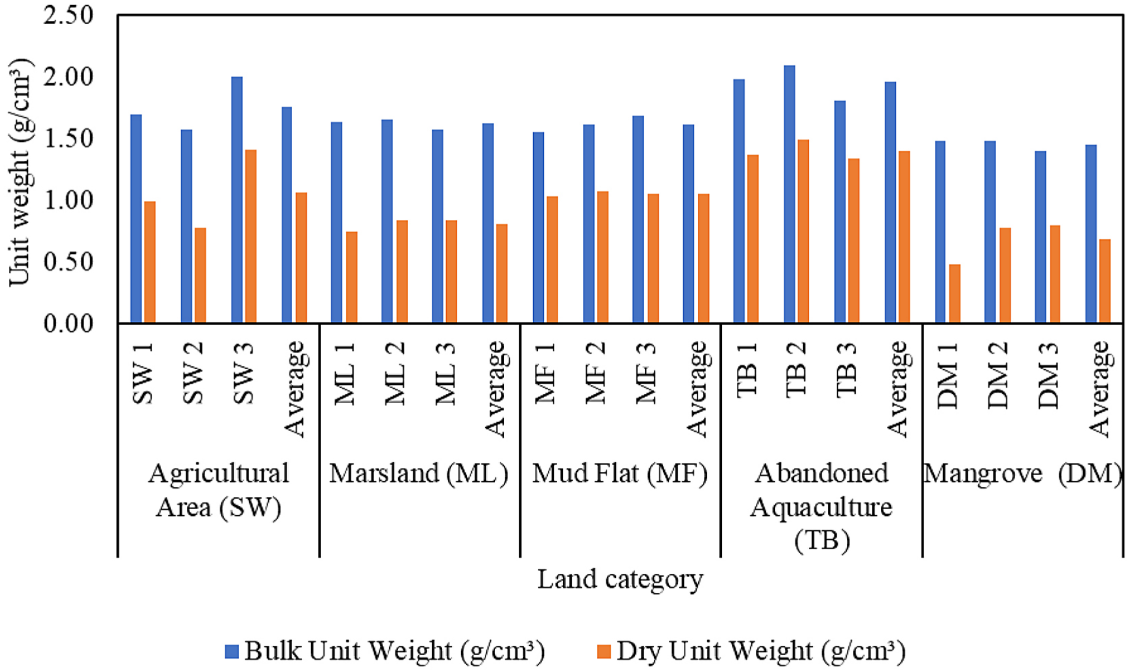

Figure 4. Comparison of bulk and dry unit weight for each location

Table 2. Summary of average unit weight for each location

Sampling location	Average bulk unit weight (g/cm³)	Average dry unit weight (g/cm³)	Difference	
			(g/cm³)	(%)
Agricultural area (SW)	1.76	1.06	0.70	66.00
Marshland (ML)	1.62	0.81	0.81	100.00
Mud flat (MF)	1.62	1.05	0.57	54.30
Abandoned aquaculture (TB)	1.96	1.40	0.56	40.00
Mangrove (DM)	1.45	0.69	0.76	110.10

and a considerable potential for land subsidence, an important factor to consider in construction planning (Alnmr et al., 2024).

Relationship between water content and unit weight

A systematic correlation was identified between water content and soil bulk density parameters. The most prominent relationship is the inverse correlation between water content and dry unit weight, with a correlation coefficient of r = –0.93 (Figure 5A). An increase in water content consistently results in a decrease in dry unit weight. This pattern is clearly observed in sample DM 1, which has the highest water content of 67.36% but the lowest dry unit weight of 0.483 g/cm³ (Figure 5B). This inverse relationship is a critical indicator of the soil's internal structure and mechanical behavior. The decrease in dry unit weight (γ_d) signifies a reduction in the mass of solid particles per unit volume of the soil, which in turn indicates a soil matrix with a high porosity and, consequently, a high void ratio (e). In soft soils, a high void ratio and high-water content are directly linked to high compressibility and low shear strength (Liang et al., 2017). High water content means the soil pores are largely filled with water, resulting in a low effective stress state. When an external load is applied, this structure, characterised by low solid content and high pore volume, is highly susceptible to significant volume reduction (consolidation) (Chao et al., 2019; Galaviz-González et al., 2022). Therefore, the strong inverse correlation (r=0.93) confirms that the wet coastal soils, particularly those in the Mangrove (DM) and Marshland (ML) areas, possess material properties highly conducive to land subsidence. Conversely, sample TB 2, with a relatively low water content of 28.98%, recorded the highest dry unit weight of 1.487 g/cm³. This pattern indicates that as soil pores become increasingly filled with water, the proportion of solid particles per unit volume decreases (Guo et al., 2023; Alnmr et al., 2024). Meanwhile, the relationship between water content and bulk unit weight also exhibits a strong inverse correlation, though it is less pronounced than that between water content and dry unit weight, with a correlation coefficient of r = –0.66. For instance, sample ML 1, with a water content of 54.39%, has a bulk unit weight of 1.63 g/cm³, whereas sample TB 1, with a lower water content of 31.05%, shows a higher bulk unit weight of 1.983 g/cm³.

In practical terms, these findings hold significant implications for sustainable land-use planning. Areas such as DM and ML, which exhibit high water content and low dry unit weight, require specific technical interventions—such as comprehensive drainage systems and soil stabilisation techniques—before they can be considered suitable for development (Ownegh, 2009; Cao et al., 2025). Conversely, areas with characteristics similar to TB and MF, which demonstrate more favorable parameters, can be developed using more conventional construction approaches. A deep understanding of these correlative relationships provides a crucial scientific foundation for mitigating geotechnical risks, particularly land subsidence, which remains a major challenge in coastal regions (Jeong et al., 2025; Muthu & Sathiyamurthy, 2025).

Grain size distribution and soil classification

The percentage of soil passing through Sieve No. 200 (< 0.075 mm) for most samples fell within the 12–50% range, while several samples from abandoned aquaculture (TB 2, TB 3) and mangrove (DM 3) fall within the 5–12% range (Table 3). The

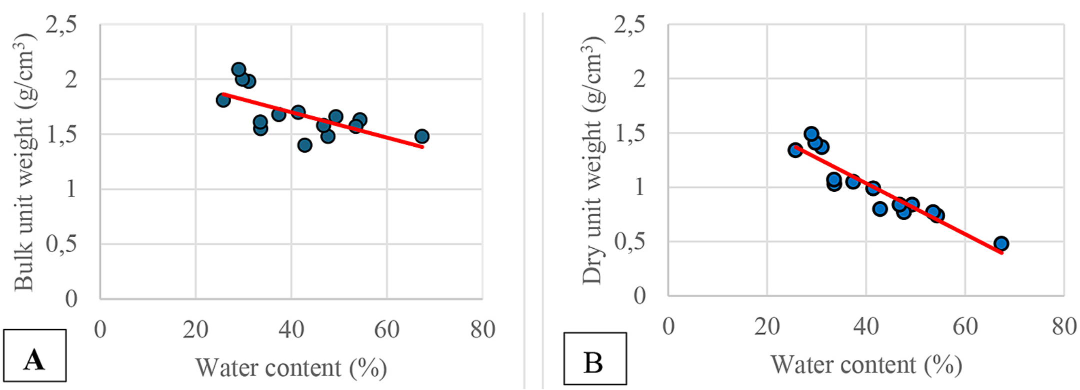

Figure 5. Relationship between water content and bulk unit weight (A) and dry unit weight (B)

fine soil fractions passing through Sieve No. 200 from each sample were further analysed using the hydrometer test to determine the proportions of silt and clay. Based on hydrometer test results, most samples are dominated by silt (62–75%) and clay (25–38%) (Table 4). According to the Unified Soil Classification System (USCS), most of the soils can be categorised as SM (Silty Sand)—coarse-grained soils dominated by sand with a significant proportion of non-plastic silt. Additionally, some samples are classified as SP–SM (Poorly Graded Silty Sand), consisting mainly of poorly graded sand with a notable amount of silt.

This classification is the most critical finding regarding the long-term geotechnical risks in the region. The predominance of silt, a fine-grained material, dictates the soil's hydro-mechanical behaviour and is the primary factor contributing to long-term consolidation settlement. Silt is characterised by low permeability, which prevents pore water from being expelled quickly when an external load (e.g., development or infrastructure) is applied. Because water cannot escape rapidly, the excess pore water pressure persists for an extended period, delaying and prolonging the soil compression (consolidation) process, which occurs slowly over many years or decades (Lo and Lee, 2015). This slow, extended compression often leads to differential settlement—variations in sinking magnitude across adjacent areas—which poses the greatest risk to structural integrity and infrastructure stability (Jeong et al., 2025). Therefore, the classification of the Denpasar coastal soils as SM, coupled with their high silt content, indicates that the main geotechnical hazard is the cumulative, long-term effects of delayed consolidation settlement, making careful foundation design and risk mitigation essential.

Regional subsurface data are critical to assessing the potential for long-term consolidation settlement. While laboratory samples were taken at 50 cm depth for near-surface characterisation across different land-use types, supplementary CPT data from adjacent areas confirmed the presence of a thick, highly compressible soft soil layer extending to depths of up to 12 m in the coastal region. The exceptionally poor geotechnical parameters observed in the shallow samples (e.g., maximum water content of and minimum dry unit weight of in mangrove areas) are thus strong indicators reflecting the high-compressibility nature of this deep, regional soft deposit (Yao et al., 2025), which is confirmed by the low cone resistance readings recorded between 1 m and 12 m (CPT 2). Therefore, the risk of significant land subsidence in Denpasar is directly attributed to the consolidation of this thick, underlying soft layer, for which the high-silt content and poor index properties of the surface soils serve as crucial proxy indicators.

Implications for sustainable coastal planning

The integration of geotechnical findings into coastal spatial planning is essential to ensure that land-use decisions in Denpasar account for the long-term behavior of soft coastal soils. The

Table 3. Results of grain size distribution analysis for soil samples

Soil sample	Sample weight (g)	Weight passing sieve no. 200 (g)	Passing sieve no. 200 (%)	Passing sieve no. 4 (%)
SW 1	20	4.43	22.19	100
SW 2	20	3.5	17.50	100
SW 3	20	3.45	17.25	100
ML 1	30	4.5	15.04	100
ML 2	30	6.76	22.54	100
ML 3	30	5.5	18.33	100
MF 1	30	4.28	14.25	100
MF 2	30	5.56	18.54	100
MF 3	30	5.53	18.42	100
TB 1	30	3.6	12.00	100
TB 2	30	2.56	8.54	100
TB 3	30	2.59	8.63	100
DM 1	30	10.26	34.21	100
DM 2	30	3.82	12.75	100
DM 3	30	3.14	10.46	100

Table 4. Results of hydrometer analysis for fine-grained soil samples

Soil sample	Silt (%)	Clay (%)	USCS classification
SW 1	64%	36%	SM
SW 2	65%	35%	SM
SW 3	68%	32%	SM
ML 1	66%	34%	SM
ML 2	68%	32%	SM
ML 3	67%	33%	SM
MF 1	63%	37%	SM
MF 2	67%	33%	SM
MF 3	65%	35%	SM
TB 1	62%	38%	SM
TB 2	65%	35%	SP-SM
TB 3	63%	37%	SP-SM
DM 1	72%	28%	SM
DM 2	75%	25%	SM
DM 3	73%	27%	SP-SM

significantly high water content, low dry unit weight, and dominance of silt-rich SM and SP–SM soil types indicate that certain land-use zones are intrinsically more vulnerable to consolidation and differential settlement. These geotechnical indicators provide a scientific basis for classifying the suitability of development across the studied land-use categories (Zhou et al., 2025).

Mangrove and marshland areas exhibit the poorest geotechnical characteristics, characterised by very high water content and low dry density, suggesting they should be prioritised for conservation or developed only with substantial soil-improvement measures (Lu et al., 2023). Building in such zones without appropriate mitigation would significantly increase the risk of infrastructure failure, long-term settlement, and service disruption due to prolonged consolidation. These areas are therefore best designated as low-intensity or green-buffer zones within coastal planning frameworks (Barrios-Crespo et al., 2023; Mashwama et al., 2025).

Mudflats and agricultural land display moderate geotechnical vulnerability. Although not as critical as mangrove and marshland soils, their silt-dominated textures and medium dry unit weight values indicate delayed pore-water dissipation under loading. Development in these areas may still be feasible but requires enhanced drainage strategies, lightweight structures, or staged preloading to reduce the risk of excessive settlement (Adesina et al., 2023). Their moderate risk profile positions them within conditional-development zoning categories.

Abandoned aquaculture ponds exhibit the most favourable soil properties for development, with relatively higher dry unit weight and lower water content. These sites represent comparatively safer zones for coastal expansion, provided that appropriate drainage and foundation planning are applied (van Bijsterveldt et al., 2020). Their geotechnical characteristics make them more suitable for conventional construction, positioning them as potential priority areas for sustainable coastal development planning (Saraswathy et al., 2016).

From a broader planning perspective, incorporating soil-vulnerability parameters into Denpasar’s coastal zoning will improve adaptation capacity to sea-level rise, reduce susceptibility to flooding and infrastructure damage, and support long-term urban resilience. The use of soil-based risk layers in spatial planning ensures that infrastructure placement, foundation design, drainage networks, and conservation strategies are aligned with the inherent behavior of coastal wet soils. This geotechnical–planning integration strengthens the scientific foundation required for sustainable coastal development in Denpasar.

CONCLUSIONS

This study set out to analyse the physical properties of coastal wetland soils in Denpasar and to assess their subsidence vulnerability as a basis for sustainable coastal planning, and this objective has been successfully achieved. By establishing a site-specific geotechnical baseline, the results clearly demonstrate that the coastal wetlands of Denpasar are highly susceptible to long-term consolidation and land subsidence. The main scientific contribution of this research lies in translating soil index properties into subsidence vulnerability and land-use suitability, addressing a critical gap where geotechnical evidence had previously not been directly linked to spatial planning decisions in Denpasar. The strong inverse relationship between water content and dry unit weight ($r = -0.93$), together with the dominance of silty sand (SM) and poorly graded silty sand (SP–SM) textures, provides a robust and practical proxy for identifying highly compressible soft soils. This interpretation is further reinforced by supplementary CPT data, which confirm the presence of a thick, soft soil layer extending to depths of up to 12 m, indicating that the observed poor surface soil properties reflect a deeper regional subsidence-prone deposit. The high silt content (62–75%) is identified as the primary factor controlling delayed pore-water dissipation and prolonged consolidation settlement. From an applied perspective, the findings reveal clear spatial contrasts in subsidence vulnerability: mangrove and marshland areas exhibit the poorest geotechnical performance and are intrinsically unsuitable for conventional development, whereas abandoned aquaculture areas show comparatively more stable conditions and greater development potential under appropriate geotechnical management. Overall, this study provides new, location-specific scientific evidence that supports the integration of soil-based subsidence indicators into zoning, risk assessment, and development suitability mapping, thereby opening prospects for more resilient and sustainable coastal development in Denpasar under increasing environmental and urban pressures.

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