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Between Natural and Anthropogenic Coastal Landforms: Insights from Ground Penetrating Radar and Sediment Analysis

Yuniarti Ulfa [1,2], Teoh Ying Jia [3,*], Ahmad Munim Che Yaziz [3], Dasapta E. Irawan [1] and Deny J. Puradimaja [1]

[1] Faculty of Earth Sciences and Technology, Bandung Institute of Technology (ITB), Bandung 40132, Indonesia; yuniarulfa@gmail.com (Y.U.); r-win@office.itb.ac.id (D.E.I.); denyjuanda@gmail.com (D.J.P.)
[2] Polytechnic of Geology and Mining AGP, Bandung 40293, Indonesia
[3] School of Physics, Universiti Sains Malaysia, Penang 11800 USM, Malaysia; bymunimyaziz@gmail.com
* Correspondence: tyj@usm.my

Abstract: Both natural and anthropogenic coastal landforms characterize Penang Island. As years have passed it is a challenge to differentiate the genuineness of landmasses created by natural geological formations or by coastal reclamation projects. An account is given of the environmental impact of solid wastes used for reclaiming land in coastal areas of Penang and of the impact of a major sewage outfall in the western channel. Leaching of heavy metals was shown to be one of the main sources of contamination from solid wastes. This paper presents eight lines of ground penetrating radar (GPR) surveys and sediment analysis to identify the anthropogenic interventions that shaped the urban landscape of Penang Island by excavations, filling, and embankment construction along the coastline and differentiate it from the natural one. The surveys were implemented in two locations, the Batu Ferringhi area, representing the natural coastline, and Persiaran Bayan Indah (the Queensbay Mall area), representing the anthropogenic coastal landform. The apparent depth of penetration that was achieved using a 250-MHz antenna is limited (less than 5 m). The results show between natural and anthropogenic sediment recorded different radar facies. In complement mode, mean grain size distribution, sorting, skewness, and kurtosis graphics of sediment samples from both sites correspond with the GPR data. This technique can likely be applied to the developing coast, where natural and anthropogenic coastal landform data is incomplete, considering future coastline development.

Keywords: GPR; Penang; anthropogenic; coastal; reclamation; landform; sorting; urban

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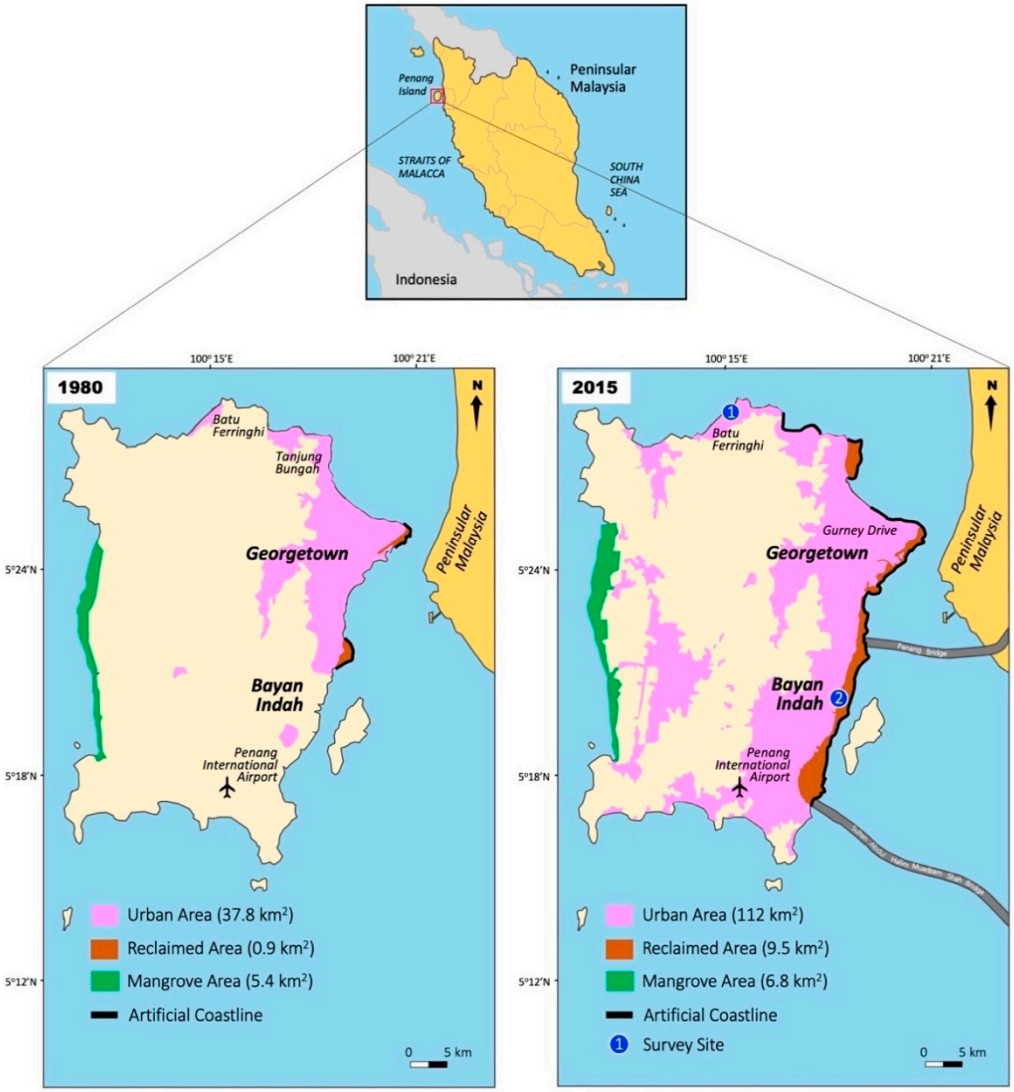
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1. Introduction

Penang is one of the most rapidly developing states in Malaysia [1]. An island represents about 300 km^2, more than half of which has a fairly rugged topography [2]. Nowadays, land availability has become a severe issue in Penang where the limited flat lowland areas of the island have already been developed for industry, which is about to exhaust the available space [3]. Meanwhile, the population growth of Penang Island demands more space for infrastructure. Since 1980, Penang's population has increased from 776,124 to 1,698,100 people in 2015 [4].

The land shortage is most popularly overcome by running coastal reclamation projects. Land reclamation is the process of creating new land from the sea [5]. Land reclamation in Penang started on a massive scale in the 1980s in response to landmass needs. That was when the manufacturing sector started to bloom in Penang [6]. As shown in Figure 1, the extent of reclaimed land increased from 0.9 km^2 (0.3%) in 1980 to 9.5 km^2 (3.2%) in 2015. The establishment of the Bayan Lepas Free industrial zone (started in 1972) made Penang the home for various multinational companies, leading to greater urbanization and greater pressure on the land [7]. Flat-lowland is a scarce resource in Penang because Penang largely has a steep topography, and the flat-lowland areas are mostly already

developed [1]. As the urban area increased from 37.8 km^2 (12.6%) in 1980 become 112 km^2 (37.3%) within 35 years, land reclamation has allowed the island to develop more buildings, infrastructures and provided additional land along coastlines that meet the high demand for flat areas in Penang island.



(**a**) (**b**)

Figure 1. Maps comparing the areal distribution (in km^2) for the urban area, reclaimed area, mangrove area, altogether with changes in anthropogenic coastal landform (reclaimed area) for: (**a**) 1980 and; (**b**) 2015 modified from [6].

Development along Penang's coastal area is still exceeding capacity. Anthropogenic interventions [8] shaping the urban landscape of Penang Island by excavations, filling, and embankment construction along the coastline are becoming intensive. Solid waste was used as filling materials for reclaiming land in coastal areas of Penang [9]. Many experts believe that this coastal reclamation process has put Penang at danger from disasters such as flooding, tsunami, ground instability, increasing saltwater intrusion, and increasing salinity in the soil and groundwater [5,10,11]. Moreover, the leaching of heavy metal contaminants from solid waste will pollute the surrounding aquatic environment, including the groundwater [9]. In an interview with Professor Emeritus Dr. Hans-Dieters Evers, he predicted the disasters would occur within 20 to 40 years after completing the new land [12].

About 30 years after the completion of the earlier massive phase of land reclamation (most of Penang's reclamation projects started at the end of the 1980s [6]), Penang is also facing water scarcity. Many developers have turned to the remaining hills to satisfy the demand for land. This has led to deforestation and the decimation of the water catchment. Teluk Bahang Dam, the largest reservoir on Penang island, has experienced droughts and lack of water supply [1]. Government efforts of seek groundwater as an alternative face environmental issues such as salinity and heavy metal contamination. The delineation between natural and anthropogenic (reclaimed) coastal landform is essential to mark the zone of possible polluted and disaster-prone land. Years have passed, making it difficult to differentiate between the island's genuine landscape due to the natural occurrence of geological formations and anthropogenic coastal landforms for which data is incomplete. The aims of this study are therefore: (a) to differentiate between natural and anthropogenic coastal landforms using the GPR technique and the sediment analysis method; and (b) to discover how ground penetrating radar (GPR) works on sediments influenced by saltwater content and sedimentary structure compaction along the coastlines.

Ground penetrating radar (GPR) is primarily designed to investigate the shallow subsurface of the Earth, buildings, bridges, discontinuities and heterogeneity using high frequency electromagnetic waves [13–15]. An antenna frequency of 500 MHz to 100 MHz gives good GPR penetration in shallow areas (less than 5 to 10 m) and provides clear images of sedimentary structures within sand [16,17]. Signal attenuation is caused by paedogenic silts, clays, carbonate, and iron oxides [17]. GPR is a fast, non-invasive method that does not require excavation [18]. GPR provides good results in highly electrically resistive sediments such as well sorted and clean sand, gravel, peat, and limestone [19,20]. Different studies have used GPR ranging from 100 MHz to 300 MHz showing good results in a sandy environment [21–23].

In this study, the GPR profiles were obtained using 250 MHz antennas at two sites (Figure 1). The results were then validated with sediment sampling and sieving analysis, as practiced in some other studies [24,25]. The alluvium at the first site in Batu Feringghi is a sandy bay with a rocky headland. In contrast, the alluvium found in site two near Persiaran Bayan Indah is mud, and there was medium and low density urban development interspersed with grassland and coconut plantations before reclamation started [9]. Studies on the geological characteristics of land reclamation or coastline progradation have received more attention lately [26–29].

2. Methods

Eight GPR profiles were collected from November 2014 to February 2015 at two sites for the coastline comparison (Figure 1). The first site is Batu Ferringhi, representing the natural coastal landform. The coordinates of its control site are 05°28′19.6″ N and 100°14′41.8″ E, respectively. Batu Ferringhi is a popular tourism beach site in Penang. It is dominated by medium to coarse-grained biotite granite of the North Penang Pluton [30]. The tropical climate has led to the igneous rocks' weathering into sandy, silty, and clayey soil. The second site, Persiaran Bayan Indah represents an anthropogenic coastal landform. The coordinates of its control site—a site specifically located in the parking lot of the Queensbay Mall, opposite to the mall are 05°19′56.3″ N and 100°18′31.5″ E, respectively.

2.1. GPR Data Acquisition

The GPR survey was conducted at the Batu Ferringhi site in November 2014. Coastal plains separated by buildings surround the geomorphology of the site. The application of ground penetrating radar (GPR) is common within the geological, environmental, glaciological, engineering and construction and forensic science fields. It is a method that uses radar signals to visualize the subsurface on a monitor. It started with the early use of electromagnetic signals and continuous-wave transmission to locate remote buried items [31]. As the technology developed, the electric properties of polar ice sheets were observed by radio echo-sounding, which was a pulsed technique [32,33]. It is then improved by

incorporating the transmission and reception of pulses by antennas with paired frequencies; the first antenna with a frequency of 500 MHz and below, and the second, 500 MHz and above. The higher the frequency transmitted into the ground, the shorter the wavelength which reduces the depth of the investigation survey but the higher the resolution. It is suitable for archaeological surveys and concrete inspection [31]. However, for engineering and geological studies, a low-frequency antenna is recommended to produce a more profound penetration but lower resolution [13,31]. In the present study, the GPR profiles were obtained using a 250-MHz shielded antenna. The maximum penetration depth is 2 m. Four survey lines were arranged perpendicular to each other like a grid. The length of the survey lines for Line 1, Line 2, Line 3, and Line 4 were 75, 76, 25.5 and 23.5 m, sequentially. Line 1 is towards the northeast, while Line 2 is towards the southwest. Line 3 is headed southeast, but Line 4 is headed northwest. The operation setting parameter of the GPR, i.e., the point interval, is 0.05 m for Line 1 and Line 3. As for the point intervals for Line 2 and Line 4, they are 0.01 m The positions of these four survey lines, including the starting and ending point for each line, are shown in Figure 2. The acquired data was then transferred from the MALA RAMAC GPR control unit to the computer using the MALA Ground Vision^{TM} software. The data were filtered several steps later for noise and unwanted signal removal [13].



Figure 2. Survey lines of GPR at site 1, Batu Ferringhi, representing natural coastal landform, plotted on Google Earth (2015), Batu Ferringhi, Penang, Malaysia. The coordinates for the initial point of survey lines (●) is 05°28′17.24″ N and 100°14′39.00″ E. DigitalGlobe 2015. http://earth.google.com (accessed on 3 February 2015).

As for the Persiaran Bayan Indah site, the GPR survey using a 250-MHz shielded antenna was performed in January 2015. The GPR penetration at this site was approximately 5 m. The four lines labeled line 5 to Line 8 stretched perpendicular to each other. Line 5 is towards the southwest, while Line 6 is towards the northeast. Line 7 is headed southeast, and Line 8 is headed northwest. The position of these four survey lines is shown in Figure 3. The point interval for Line 5 and Line 7 is 0.05 m, but it is 0.01 m for Line 6 and Line 8.

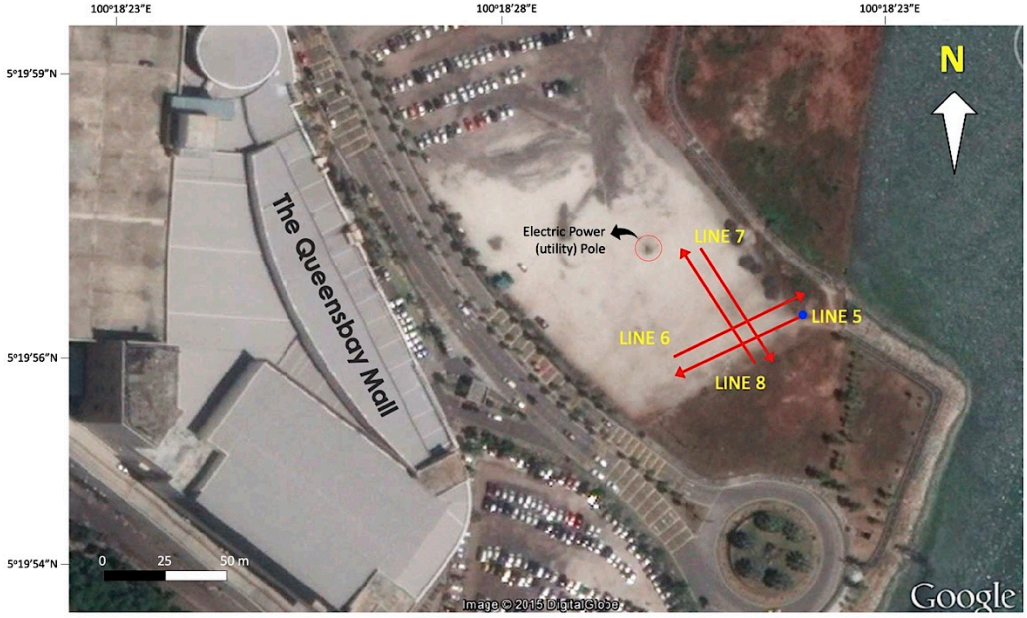


Figure 3. Survey lines of GPR at site 2, Persiaran Bayan Indah, Bayan Lepas representing anthropogenic coastal landform, plotted on Google Earth (2015), Persiaran Bayan Indah, Penang, Malaysia. The coordinates for the initial point of survey lines (●) is 05°19′57.19″ N and 100°18′30.23″ E. DigitalGlobe 2015. http://earth.google.com (accessed on 3 February 2015).

2.2. Sieve Analysis

GPR has been used in this study to understand the shallow subsurface of natural and anthropogenic coastal landforms. However, GPR facies are not equal to sedimentary facies. To correctly recognize the sedimentary characteristics, it is common to combine the detection of sedimentary strata with sediment sample analysis because the grain size distribution can reveal the characteristics of a dynamic sedimentary environment more accurately. Soil reconstruction is the core technique of land reclamation. As artificially assembled soil, the spatial distributions of reclaimed soil properties are different from those of natural soil since the parent materials of reclaimed soil are highly random. Therefore, the different grain size distribution patterns can indicate natural and anthropogenic coastal landforms, respectively [34].

Sieve analysis is a procedure to sort the grain size according to their diameters settled through a mechanical technique according to its weight [35]. The sieve materials were acquired by taking samples from the survey area. The samples were taken randomly but along the site's survey lines, using a cylinder bottle as a container, and placed into a plastic bag.

Five sediment samples were collected from the Batu Ferringhi site, then another five were collected from the Queensbay Mall parking lot site. The raw data of these ten sediment samples can be accessed online (open access) from https://doi.org/10.5281/zenodo.4395755, accessed on 11 April 2021.

In the laboratory, the samples were placed in a beaker and washed with water. The samples were stirred using a spatula, and these steps were repeated a few times until it became apparent few impurities remained. The water was then removed. In the next step, the samples were dried in a drying oven set at 80 °C for 2 to 3 days. After the samples were completely dry, the dried samples was set up for sieving. The sieves' empty weight is determined as sieves with increasing mesh size are put on the pan. The sample is weighed and placed on the uppermost sieve, which is −2.5 Φ unit. The complete sieve stack was then placed on the sieve shaker and fastened. Ten minutes sieving time on the sieve shaker was set, and when the sieving time has stopped, the collecting pan and the fraction on it were weighed. The mass of each fraction is determined, recorded, and calculated in the Microsoft Excel application, then plotted on a graph.

The most straightforward task for the grain analysis from the graph is the measurement of the central tendency, which is commonly measured for sieved samples as a central tendency, including median, mode, mean, kurtosis, and skewness. The frequency curve measures the central direction, including median, mode, and mean [36]. Percentages of coarse grain or fine grain can show up significantly as horizontal limbs at the ends of the curve. Cumulative curves are powerful to express sorting. Sorting is the tendency for the grains to arrange in one class of grain size. Half of the particles by weight are coarser than the median and half are finer, so the the diameter corresponds to the cumulative frequency curve's 50% value. It may be expressed either in phi (Φ) or in millimeters (mm). The mode is the most frequently-occurring particle diameter corresponding to the steepest point on the cumulative curve. It also corresponds to the highest point on the distribution curve. Graphical mean (M) is the best measure for determining the overall size. At the same time, graph kurtosis (K), a grain size frequency curve, is termed the degree of "peakedness," whereby curves which are more peaked than the normal distribution curve are termed "leptokurtic." Those which are looser than the normal are said to be "platykurtic" [36].

3. Results

3.1. Site 1, Batu Ferringhi's GPR Profiles

Four GPR profiles oriented perpendicular to each other along the natural coastal landform are described and interpreted. Each profile will be discussed separately. The interpretation was observed based on the anomaly patterns of the profiles. They show the subsurface characteristics of the site.

3.1.1. Line 1

This is the southeasternmost of the four profiles (Figure 2). It runs from SW to NE across the Batu Ferringhi coastline and is 75 m long. The site is near a public toilet connected to an underground pipeline system shown in Figure 4a. The result shows two clear reflection events (red and yellow lines) observed at a depth of less than 1 m and less than 2 m, respectively (Figure 5a). A clear radar signal is seen on the upper part of the profile, which is 2 m in depth. It starts to show a blurred image afterward. At the start of the line, between 0 m and 12 m, and at the end of the line, between 69 m and 75 m (marked in blue boxes), until the depth of maximum 2 m, the conditions seem to be very dry as the reflector observed. However, more significant than this depth, between 12 m and 68 m, the radar signals are starting to attenuate, resulting in lost radar signals in the GPR profiles.



Figure 4. Noise during the GPR survey. (**a**) Anomalies in line 1 because of the existing public toilet including its underground pipeline system and well; (**b**) Man-made structure which is stairs made from concrete disrupted the wave activity and create sediments inclination in line 3, and (**c**) signal noise in line 8 resulted from the underground electrical wiring cable of the existing utility (power) pole. Refer to Figures 2 and 3 for detail positioning on the map.

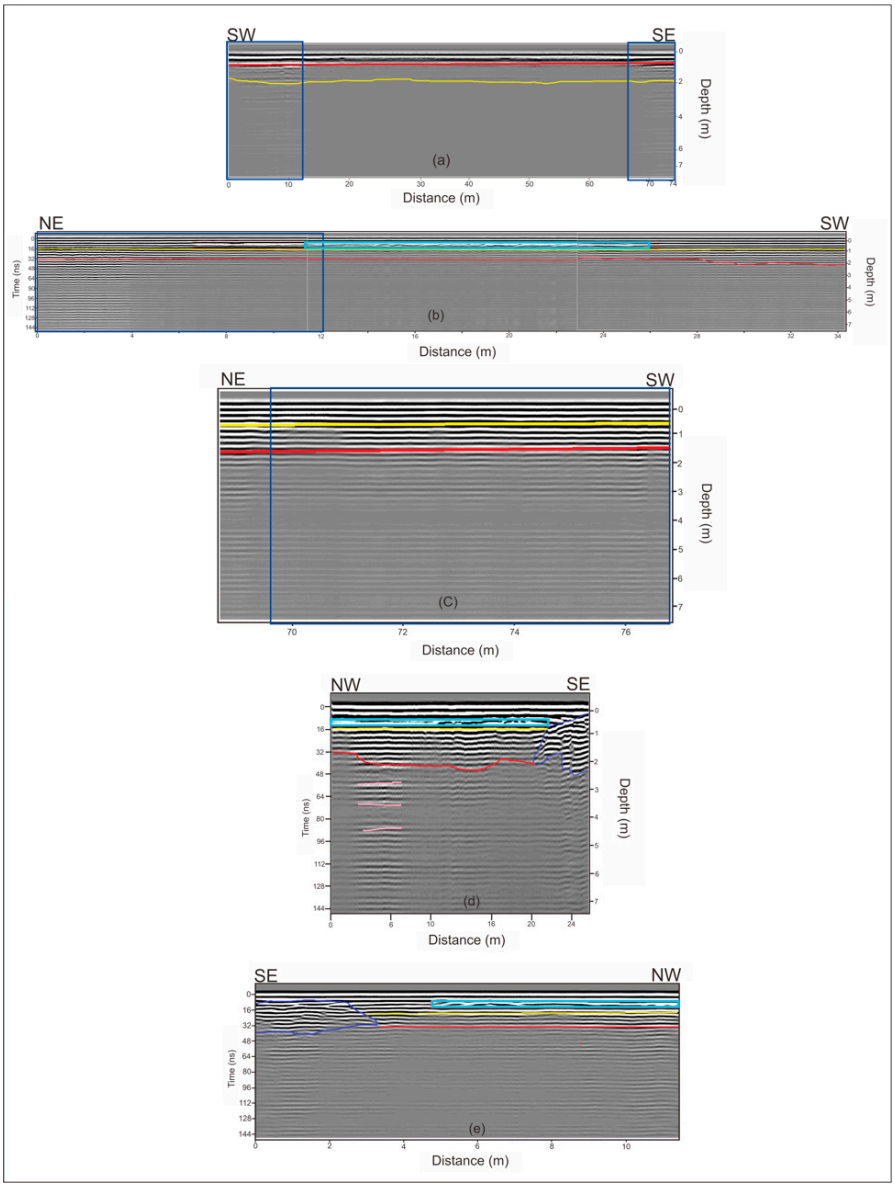


Figure 5. GPR profiles at site 1, Batu Ferringhi Beach, representing natural coastal landform. (**a**) Line 1-Anomalies in between 12 m and 68 m as indicated by attenuation until lost radar signal is due to the existing public toilet, its underground pipeline system, and well; (**b**,**c**) Line 2–a 0.5 m thick compact layer detected along with the distance of 6.5 to 26.5 m, interpreted as a saturated zone. In correspond with line 1, the interpreted dry condition zone is marked in between 0–12 m and 69–76 m; (**d**) Line 3–starts from the distance of 21 m shows sediments inclination upwards due to the man-made structure which may have been disrupted the wave activity; (**e**) Line 4–also shows the indication of the man-made form at a depth of <1.5 m and <2.5 m respectively connect to the features as delivered in line 3—all saturated zones marked by cyan boxes, while dry sediments marked by blue boxes. Saturated zones interpreted as groundwater level estimated approximately at a depth of 1.5 m.

3.1.2. Line 2

This line is the northwesternmost of the four profiles 2 (Figure 2). Its actual length is 76 m and it runs from NE to SW. The point interval of 0.01 m makes the profile longer compared to line 1. Therefore, in Figure 5b,c, only some anomalies are marked on Line 2. In this section, at a depth of 0.5 (cyan box), the visible reflection is considered a saturated zone where the reflection seems compact with two different upper and lower layers. The thickness of this zone is about 0.5 m, observed in parallel from the distance of 6.5 m.

Then the reflector indicates some dipping events as it slowly increases in depth, and the compaction stops at the distance of 26.5 m. Corresponding with Line 1, the blue box is marked from 0 m–12 m and 69 m–76 m until the maximum penetration of more than 2 m depth interpreted as dry conditions, respectively.

3.1.3. Line 3

Line 3 (Figure 2) is 25.5 m long. It is the most southwestern of the profiles. The point interval of the GPR antenna is 0.05 m and shows two clear reflection events (yellow and red lines) observed at depths < 1.5 m and <2.5 m, respectively, where the reflectors are undulating (Figure 5d). Clear radar signals are seen at the upper part of the profile, which is <2.5 m, and a blurry image starts to show with an average thickness of 2 m. The saturated zone, as interpreted, is in the cyan box at a depth of 1 m. In this section, at a depth of 0.5 m, it is seen from the radargram that at a distance of 21 m, the sediments inclined upward as there is a man-made structure that disrupts the wave activity. It suggests that the more recent sand closer to the man-made design may exhibit a higher wave activity shown in Figure 4b.

3.1.4. Line 4

The length of this survey line is 23.5 m (Figure 2). It is the northeasternmost of the profiles. Like Line 2, the antenna's point interval is 0.01 m at a depth of <1.5 m and <2.5 m, respectively, and the reflector shows undulation. As seen at a depth of 0.5 m from the front part of the line, some inclination is due to the man-made structure that exhibits a lower wave activity (Figure 5e). Clear radar signals are observed at the upper part of the profiles, which are <2.5 m, and start to show a blurry image with an average thickness of 2 m. A visible reflection can be considered the saturated zone of the area where the reflection seems compact with two different characters at a depth of >1 m (cyan box).

3.2. Site 2, Persiaran Bayan Indah's GPR Profiles

The four GPR profiles (Line 5 to Line 8) were set perpendicular to each other along the anthropogenic coastal landform. The coastline functioned as the parking lot for the Queensbay Mall and city park. Characteristics and anomalies of each line are described below.

3.2.1. Line 5

Figure 3 shows that Line 5 extends about 65 m in length from NE to SW across the anthropogenic coastal landform. It offers three clear reflection events (yellow, red, and pink lines) observed at a depth of <2 m, <3.5 m, and <4.5 m, respectively. A clear radar signal is seen in the upper part of the profiles, which is less than 2 m and starts to show blurred image characteristics with an average thickness of 2 m. Deeper than 4.5 m, the radar begins to attenuate, resulting in lost radar signals in the GPR profiles. Based on the objective of obtaining an idea of how the subsurface in the anthropogenic coastal landform of Penang Island differs from the natural one, the presence of the reclamation subsurface is indicated by the undulating reflector (green line) at the 1.5 m depth as it follows throughout the survey line (Figure 6a).

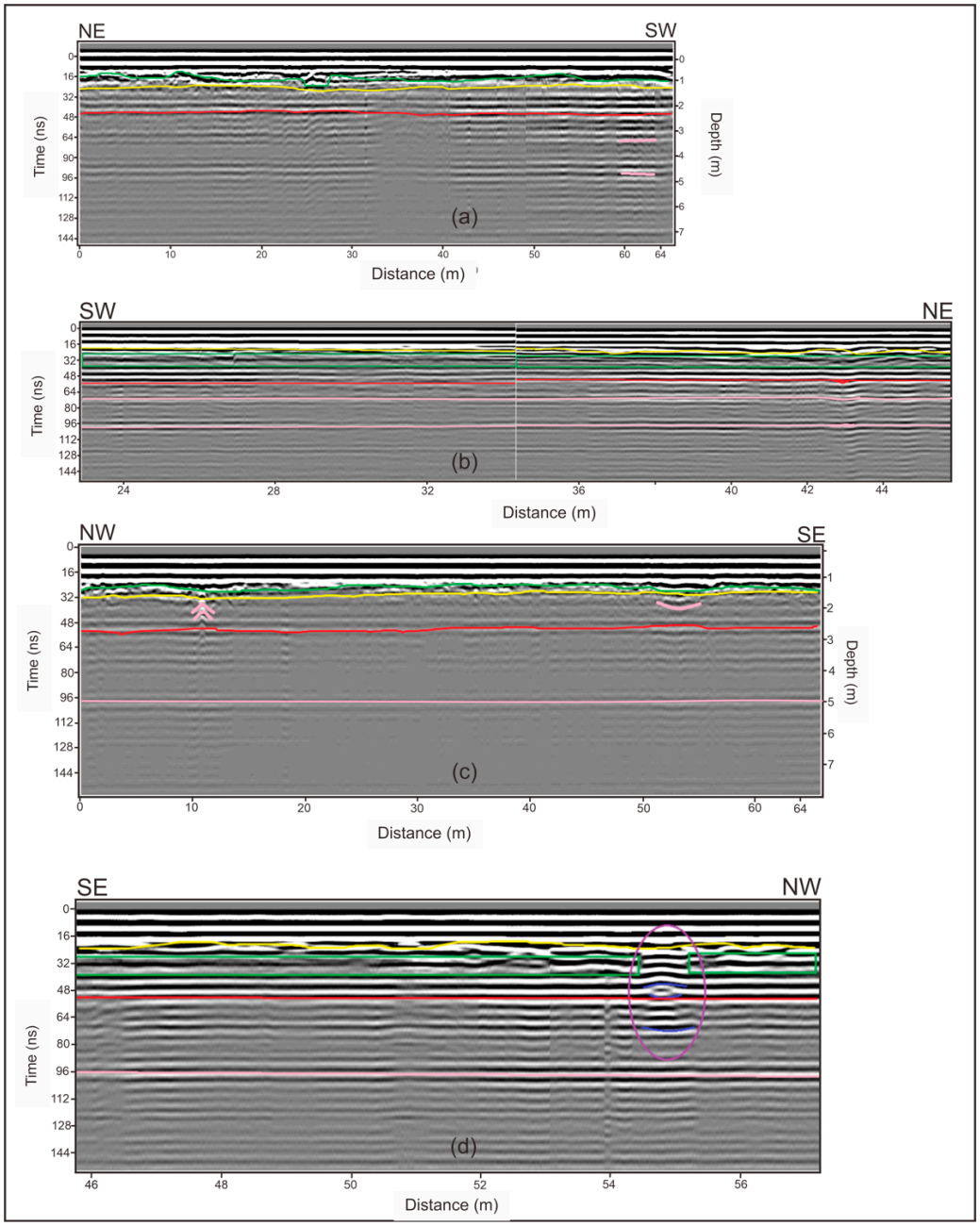


Figure 6. GPR profiles at site 2, Persiaran Bayan Indah (in front of the Queensbay Mall), representing anthropogenic coastal landform. (**a**) Line 5-Anomalies on the surface as shown as undulating green line interpreted as the upper reclamation subsurface; (**b**) Line 6–at a depth of 1.5 m, the undulating reflectors corresponds to top filling sediment, and there are tiny reflections that penetrate through as the unsaturated reclamation area. Another reflector at a depth of 2 m (red line) is interpreted as the water table; (**c**) Line 7–corresponds to lines 5 and 6, the green undulated line found at a depth of 1.5 m interpreted as top of aggregates filling. At the distance of 11 m, 16 m, and 53 m, suggests more resonant penetrated signals due to the man-made structure, could be coming from pipework from the Queensbay mall to the sea; (**d**) Line 8–noise (purple circle) at the distance of 54 m, where the signal penetrated more in-depth into the profile due to the electrical motion from the underground wiring that connected to an existing utility pole on the site.

3.2.2. Line 6

Line 6 extends 65 m from SW to NE along the coastline (Figure 3). The point interval of the GPR antenna is 0.01 m makes the profile longer compared to Line 1. Figure 6b

only shows part of it. Three clear reflection beds (marked as yellow, red, and pink lines) were observed at depths < 1 m, <3 m, and <6 m, respectively. Clear radar signals are visible on the upper part of the profiles, which is less than 5 m depth, and start to show the characteristics of blurred images with an average thickness of 1 m. At a depth of 1.5 m, it is possible to see a reflection that may correspond to top sediments (Figure 6b). There are tiny reflections that penetrate through the unsaturated reclamation area. Another reflector at depth 2 m observed along the survey lines (red line) is interpreted as the water table. The reflector can penetrate below and reflect another signal to the antenna. Another reflector is observed at a depth of 3.5 m, which is relatively parallel to the previous but undulating, followed by another reflector at a depth of 5 and 6 m (pink lines). The thickness of this layer is approximately 3.5 m, with some dipping events being observed.

3.2.3. Line 7

Figure 3 shows that Line 7 extends about 65 m long from NW to SE across the anthropogenic coastal landform. The point interval of the GPR antenna is 0.05 m, and the results show three clear reflection events (yellow, red, and pink lines) at a depth of <2 m, <3.5 m, and <5 m, respectively. All reflectors are undulating, as shown in Figure 6c. A clear radar signal is observed on the upper part of the profiles, which is less than 3 m, and starts to show a blurry image with an average thickness of 1 to 2 m. The radar begins to attenuate deeper than 5 m depth, resulting in lost radar signals in the GPR profiles. The presence of the undulating reflector (green line) at the 1.5 m depth indicated the reclamation upper subsurface, as it follows throughout the survey line at distances of 11 m, 16 m, and 53 m, which suggests that signals penetrated more in-depth into the profile due to the man-made structure, which exhibits a higher wave activity (pink line). Therefore, it is apparent that the front's inclination is determined by the received signals, such as the pipework from the Queensbay Mall.

3.2.4. Line 8

The Line 8 survey line length is 65 m, extending from SE to NW across the anthropogenic coastal landform (Figure 3). It shows three clear reflection events (yellow, red, and pink lines) observed at depths of <1.5 m, <2.5 m, and <5 m, respectively. The point interval of 0.01 m is more visible and apparent for anomalies and reflections but it shows a more extended profile. Figure 6d only shows part of the line. Clear radar signals are observed at the upper part of the profiles, which is less than 5 m, and then they start to show a blurry image with an average thickness of 1 m. The reclamation subsurface is indicated by the undulating reflector at the 1.5 m depth, as it follows throughout the survey line (green line). At the distance of 40 m, the front's inclination is determined by the received signals, such as the pipework. At the length of 54 m, the signal penetrated more in-depth into the profile while diffracting and reflecting on the surface. This is due to the electrical motion, which may exhibit a higher wave activity (purple circle). Therefore, there must be electrical wiring cable underground that is assumed from an existing pole utility on the site, as shown in Figure 4c.

3.3. Sieve Analysis of Site 1, Batu Ferringhi

Five sediment samples were collected at this site. They are namely samples BF1, BF2, BF3, BF4, and BF5. These samples compare the weight of sediments (%) and grain size (Φ or phi unit). The grain size mode, graphic means (M), graphic standard deviation (D), graphic skewness (S), and graphic kurtosis (K) were then calculated for all the samples. The grain size classification refers to the Krumbein phi-scale, a modification of the earlier Udden-Wentworth scale, a millimeter-based-scale with a constant ratio between class limits [37]. The phi scale emphasizes a finer grain size—the Wentworth grain size scale corresponding to the phi-scale shown in Figure 7. The frequency curves of each sample are shown in Figure 8. An analysis of these frequency curves is summarized in Table 1 below.

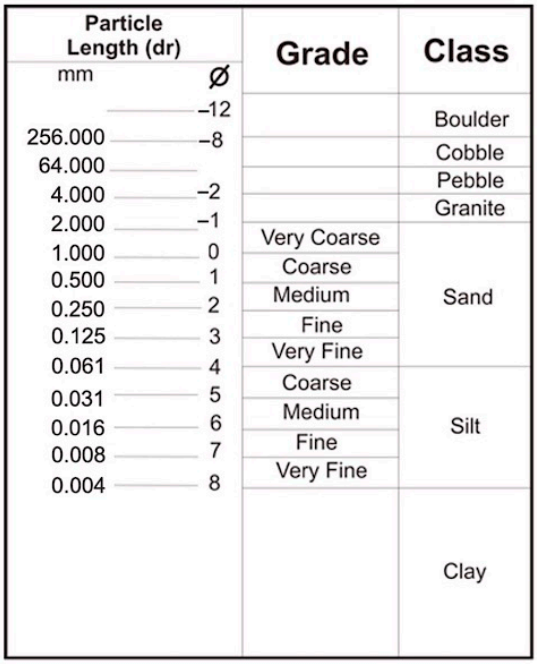


Figure 7. Widely used Udden-Wentworth grain size scale (modified from [38]). Grain size for sediments sample from Batu Ferringhi ranging from −2.5 Φ (pebble) to 4 Φ (very fine sand).

Table 1. Summary on analysis of the five sediment samples' frequency curves in Batu Ferringhi, representing natural coastal landform sediments.

Sample	Mode	Graphic Mean (M)	Graphic Standard Deviation (SD)	Graphic Skewness (S)	Graphic Kurtosis (K)
BF1	−0.5 Φ	Very coarse sand	Moderately sorted	Near symmetrical	Leptokurtic
BF2	1 Φ and 1.5 Φ	Medium sand	Moderately sorted	Near symmetrical	Mesokurtic
BF3	1 Φ	Coarse sand	Moderately sorted	Negatively skewed	Leptokurtic
BF4	1 Φ	Coarse sand	Moderately well-sorted	Near symmetrical	Leptokurtic
BF5	−0.5 Φ and 0.25 Φ	Gravel	Moderately sorted	Positively skewed	Platykurtic

3.4. Sieve Analysis of Site 2, Persiaran Bayan Indah (the Queensbay Mall Area)

Five sediment samples were collected at this site. They are namely samples QB1, QB2, QB3, QB4, and QB5. The frequency curves of each sample are shown in Figure 9. The analysis of these frequency curves is summarized in the following Table 2.

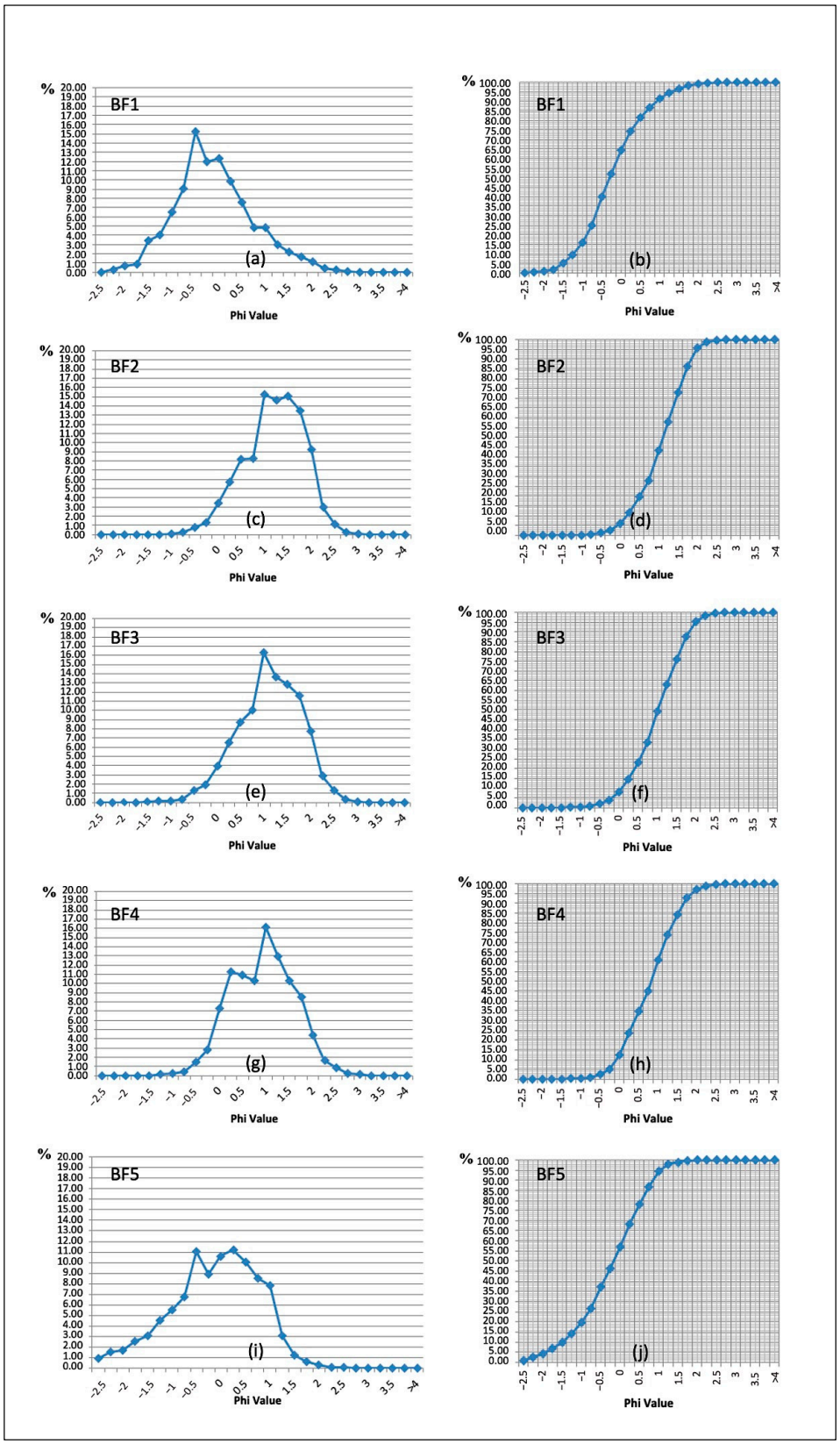


Figure 8. The Batu Ferringhi samples' grain size distribution trend is shown in the figures labeled as (**a**,**c**,**e**,**g**), and (**i**). The grain sample's cumulative frequency is shown in the figures labeled as (**b**,**d**,**f**,**h**), and (**j**)—these five samples, BF1 to BF5, representing the original sediment accumulation along the natural coastal landform.

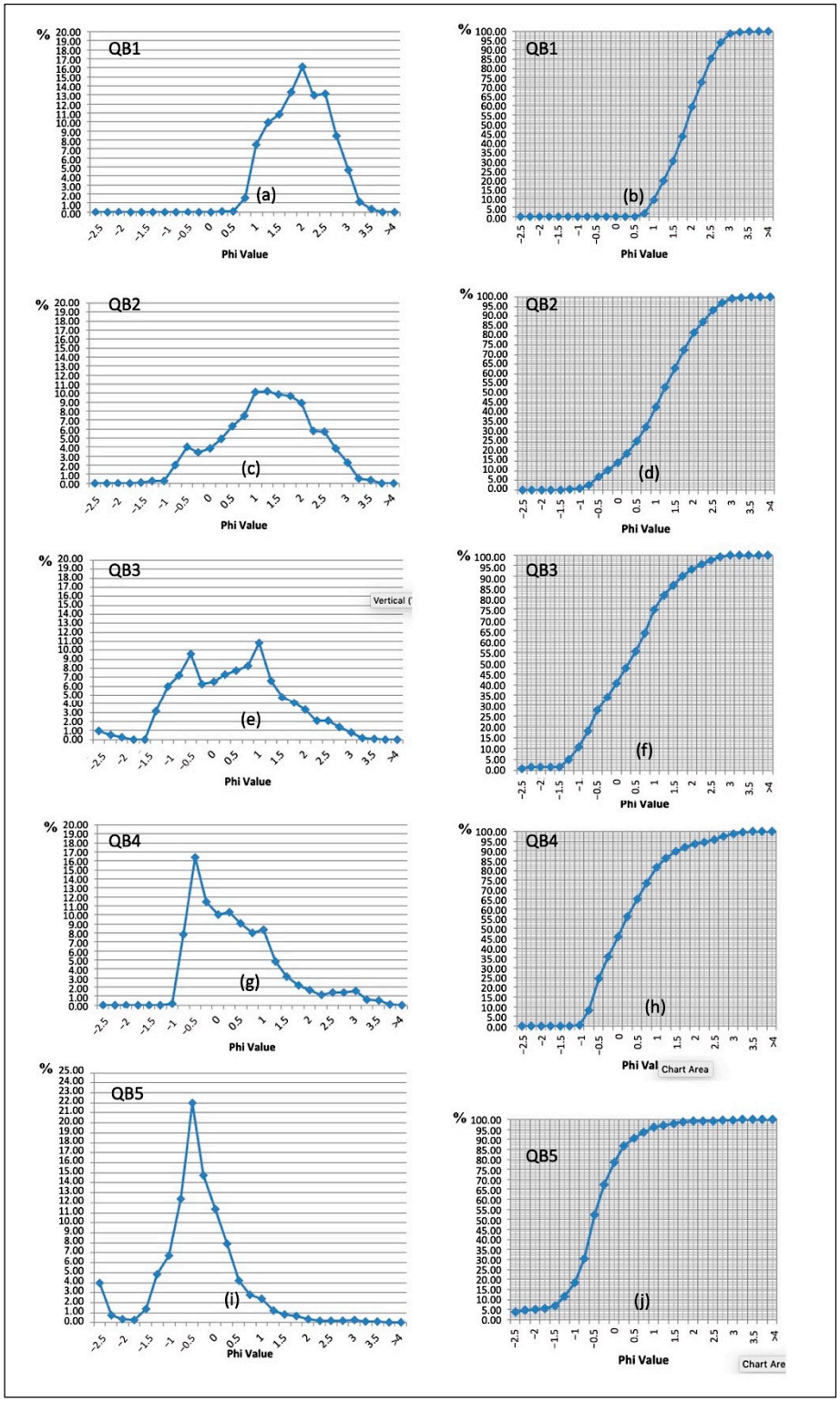


Figure 9. The Persiaran Bayan Indah (the Queensbay Mall) samples' grain size distribution trend is shown in the figures labeled as (**a**,**c**,**e**,**g**), and (**i**). The grain sample's cumulative frequency is shown in the figures labeled as (**b**,**d**,**f**,**h**), and (**j**)—these five samples, QB1 to QB5, representing the dumping sediment along the anthropogenic coastal landform coastline.

Table 2. Summary on analysis of frequency curves of the five sediment samples in Persiaran Bayan Indah (the Queensbay Mall area), representing the sediments of anthropogenic coastal landform or reclamation coastline.

Sample	Mode	Graphic Mean (M)	Graphic Standard Deviation (SD)	Graphic Skewness (S)	Graphic Kurtosis (K)
QB1	2 Φ	Medium sand	Moderately well-sorted	Negatively skewed	Platykurtic
QB2	1 Φ	Medium sand	Poorly sorted	Near symmetrical	Mesokurtic
QB3	−0.5 Φ and 1 Φ	Coarse sand	Moderately sorted	Near symmetrical	Mesokurtic
QB4	−0.5 Φ	Coarse sand	Moderately well-sorted	Near symmetrical	Leptokurtic
QB5	−0.5 Φ	Very coarse sand	Moderately sorted	Near symmetrical	Leptokurtic

3.5. Correlation between Batu Ferringhi and Persiaran Bayan Indah

Figure 10a,b show the data correlation of grain size and cumulative frequency of samples at Batu Ferringhi. In comparison, the data correlation of grain size and cumulative frequency of samples at Persiaran Bayan Indah (the Queensbay Mall area) are shown in Figure 10c,d. The five samples from Batu Ferringhi display an even grain size. The graphic mean varies from medium sand to gravel. The sorting sample is mostly moderately sorted and increases to well sorted. The samples are primarily near-symmetrical in their grain size distribution pattern. The graphic kurtosis is mostly leptokurtic. These data indicate that sediment along the natural coastal landform is homogenous and the grain sizes are distributed evenly.

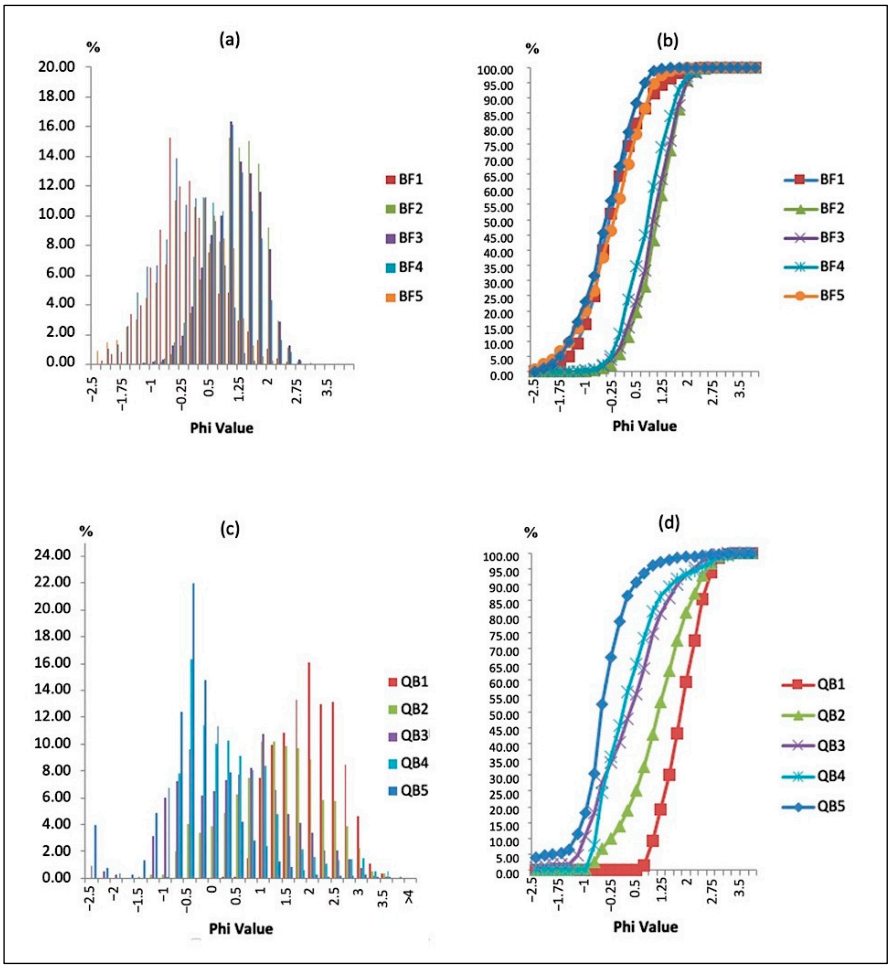


Figure 10. Comparing grain size and cumulative frequency of samples at Batu Ferringhi (**a**,**b**) and Persiaran Bayan Lepas (**c**,**d**).

The five samples from the Persiaran Bayan Indah (the Queensbay Mall area) consist of varying grain sizes. The mean size varies largely from medium sand to very coarse sand. In contrast with samples from the Batu Ferringhi, which are relatively well sorted, in Persiaran Bayan Lepas, the sorting is mostly moderately to poorly sorted. It shows unclear trends for the sample content, which means the sediments dumped on the anthropogenic coastal landform are heterogeneous.

4. Discussion

The Malaysian coastline varies from scenic bays flanked by rocky headlands to shallow mud flats buffered by mangrove forests [11,29]. However, there are some differences between the East Coast of Peninsular Malaysia and the West Coast. The coastline setting for the East Coast is a hook-shaped sandy bays because of the high sediment yield from river discharge confront the harsh wave environment, whilst mild wave climate of the Straits of Malacca makes wide mud shores in the West Coast and coastal forest-rich biodiversity [11].

The present study area covers part of the West Coast. However, the two study sites have different natural sediment characteristics (Figure 11). Site 1, Batu Ferringhi, is located on the north coast of Penang Island of the western coast of Peninsular Malaysia on the Malacca Strait. The tidal range in this site is microtidal (less than 2 m) [39]. The site is surrounded by Triassic biotite granite, which weathering product is manifested in the shore sediment, mixing with sand, silts, and even shells with some patches of gravel and granite boulders [9,11,39].

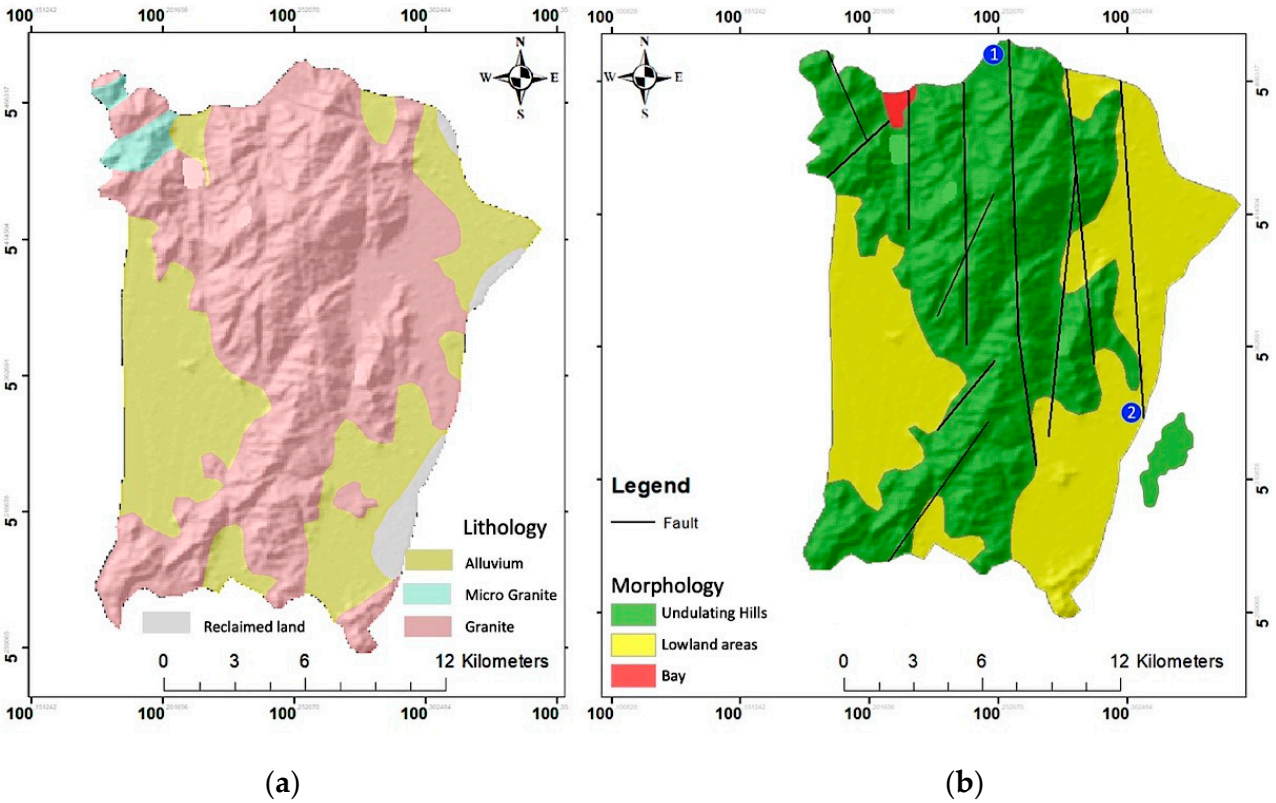


Figure 11. Comparison between (**a**) lithology map (modified from [40]) and (**b**) geomorphology map of the overall Penang Island. Both sites are beach landforms. Symbol 1 and 2 represent the survey site 1 and survey site 2.

Meanwhile Site 2, Persiaran Bayan Indah, is anthropogenic land. It is located on the southeast coast of Penang Island on the western coast of Peninsular Malaysia on the Malacca Strait, facing east towards Jerejak Island. The area is protected from waves. The natural sediment before reclamation was composed of wide mud from the river discharge [9]. The existence of Jerejak Island makes the deposition of mud wider in this area.

Batu Ferringhi (Site 1) is considered an undisturbed beach landform. The sediment deposition is natural, compact, and continuous. The GPR survey on this natural coastal landform shows flat compaction along the profiles; strong and continuous reflectors; a saturated zone as indicated by the reflection seems to be compact with two different upper and lower layers (cyan boxes as seen in Figure 4b); radar signals penetration is limited (less than 2 m); at a depth of more than 2 m dry conditions were indicated and the signals started to blur. The interruption of a man-made structure naturally forms a cross-sedimentary bedding structure (Figure 4). Indeed, the GPR method can be used further to analyze processes such as sediment depositional processes as claimed by [41].

The GPR responses in the coastal reclaimed land (Site 2) are very different. Here, the anthropogenic coastal landform shows undulating reflectors (green lines as seen in Figure 5). The surface layer with a flat surface and an undulating bottom at the scale of meters to hundreds of meters is widespread and typical of anthropogenically-affected fluvial depositional environments [42]. Discontinuous reflectors are visible in certain parts due to utility pole penetration or human activities; radar signals penetrated deeper (approximately 5 m), so it reveals more reflectors; at a depth of 1.5 m reflections corresponding to top filling sediments with some tiny reflections that penetrate through as the unsaturated reclamation area as seen. As seen in Figure 6a–d (Site 2), the three clear reflectors are the main characteristic of anthropogenic landform. Anthropogenic coastal landforms undergo a two to three times filling process followed by foundation treatment [43]. The first filling material is called the subgrade. When the subgrade material compacts after a certain period, the subsequent filling called sub-base is dumped on the first filling material. The process is repeated for the third filling material called a base layer. The three clear reflection events indicate this sub-grade layer, sub-base layer, and base layer of the reclaimed land [44].

GPR penetration in the natural coastal landform is shallower than in the anthropogenic coastal landform because of attenuation caused by the saltwater intrusion on Batu Ferringhi beach, while the saltwater content in the filling reclamation sand of the Queensbay Mall area is not that much since it is anthropogenic and less exposed compare to the natural coastline. Hence, it is less influenced by signal attenuation.

The use of sieve analysis gives evidence to confirm the previous GPR conclusions about the differences between the natural and anthropogenic coastal landforms. At Batu Ferringhi, which represents the natural coastal landform, although the sediment grain size ranges widely from medium sand to gravel size, they are evenly distributed. Other characteristics of such a sediment is the heterogeneous sediment visible as gravel content [45]. The even distribution is moderately sorted to well sorted at every sampling point. Natural sedimentation makes it possible for the sediment materials to sort evenly over time. As the Batu Ferringhi area is laid by medium to coarse-grained biotite granite or Ferringhi granite [2], the sediments along the coastline correspond to the weathering transportation product of this formation. The progradation characteristics of Malaysia's West Coast, including in Penang, formed a reverse grading of sediments, including gravel in the deposits. Unfortunately, the stratigraphic reverse graded bedding of deposition was not clearly recorded in this study.

This is different from an anthropogenic coastal landform, represented by the Persiaran Bayan Indah (the Queensbay Mall area), where the site displays an uneven grain size distribution. This frequency distribution can be seen from the graphic skewness and kurtosis. Reclamation sediment ranging from medium to very coarse sand and mostly poorly sorted in the middle, is moderately sorted at the starting point and the end. This shows unclear trends for the sample content. Substantial variability of texture was observed since it is a filling material for coastal reclamation.

5. Conclusions

As mentioned earlier, this study's main objective was to distinguish between an anthropogenic coastal landform (reclamation) coastline and a natural one using the GPR technique and sediment analysis method. The result of this study gives excellent feedback

to achieve this objective. Based on Penang Island's GPR technique, the results show that the coastline in Persiaran Bayan Indah, specifically in front of the Queensbay Mall, has the characteristics of reclamation land such as undulating and clear reflection events, which are very different from the Batu Ferringhi coastline, a natural coastal landform with flat compaction along with profiles, strong and continuous reflectors. Sieve analysis shows the sediment grain size ranges widely from medium sand to gravel size with evenly distribution on the Batu Ferringhi coastline and uneven grain size distribution on the Persiaran Bayan Indah coastline.

These findings can be applied further as a model to recognize both natural and anthropogenic sedimentation because both coastal landforms have different physical and engineering properties (material composition, compaction, sedimentary structures, and textures). These models might help engineers delineate the hazard-prone zones of reclaimed land due to groundwater salinity, ground instability, and polluted land and differentiate it from the natural coastal land. Besides GPR and sieving analysis, possible trenching and groundwater-well sampling of the study area will be helpful to enhance this comparison model in the future.

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