Impacts of Coastal Development on the Shoreline Change of the Eastern Gulf of Thailand

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Abstract. The Map Ta Phut (MTP) Port has been developed on the middle portion of the Rayong Bay, Thailand, since 1992. After the expansion of the port completed in 2002, the port has an approximately 3.5 km wide and extending 4.0 km seaward. This paper provides the assessment of the construction of the MTP Port project on the shoreline of the Rayong Bay. Historical shoreline positions were extracted from aerial photography and satellite imagery taken between 1957 and 2016 using ArcGIS version 10.4. The rates of shoreline changes pre- and post-port development were implemented using the Digital Shoreline Analysis System (DSAS). Results indicate that the Rayong Bay shoreline mostly was in dynamic equilibrium with an average rate of less than 0.5 m/y prior the construction of the MTP port. After the completion of the port, a significant shoreline accretion has continuously been found along the shoreline of about 500 m adjacent to both sides of the port. Meanwhile, the Rayong Bay shoreline had been eroded about 28 % of the total shoreline after the port completed in 1992 and increased to 30% after the port expansion in 2002. Coastal protection structures included seawalls, segment breakwater, Y-shaped groins, and jetty were applied along the receded shore. Most of those structures have successfully stabilized the shoreline, and the Rayong Bay has likely reached a new dynamic equilibrium since 2011.

1. Introduction
Coast is one of the most dynamic features on the earth’s surface because its shape is controlled by interaction among atmospheric, ocean and land surface systems [1]. Coastline continuously migrates landward or seaward over a various time scale in response to sea level, wave conditions, weather climate, and seasons [2]. In modern society, the coasts are highly valuable in many ways, for instance, as sites for port and harbour facilities, as locations for industrial processes, as sites for tourism, as productive and richest habitats for fish and other marine life, and more than 40% of the world’s population nowadays live along the coasts [3]. Such significant coastal developments normally must be protected from any change in shoreline position, and coastal defenses play a vital role in protecting those human assets [1]. However, improper uses of coastal protection structures (seawalls, breakwaters, groins, ripraps, etc.) may produce some adverse consequences in coastline erosion processes and environment [4] [5] [6]. Therefore, post-construction monitoring is an important task to evaluate the impacts of a coastal development project and the effectiveness of erosion-controlling measures. [7] [8] [9].
In the eastern Gulf of Thailand, the Map Ta Phut Industrial Estate project has been developed since 1989 as the greatest base of petrochemical industries in Thailand [10] [11]. The Map Ta Phut (MTP) port was constructed on the middle portion of the Rayong Bay (Figure 1) as a component of the largest industrial estate in the country [12]. After the construction of the port, land reclamation, and infrastructures, severe erosions near the port were reported [11] [13]. To diminish shoreline recession due to existing of the MTP port, many types of coastal protection structures have been applied to the Rayong coast during the period 2000-2004 [14]. The objective of this paper is to document the effects of the construction of the MTP port and its coastal protection projects on the Rayong bay’s shoreline using remote sensing technique. Results of this study are intended to facilitate future coastal zone planning and management along the Rayong bay and provide a better understanding of the dynamics of the shoreline in response to the coastal development activities.

![Figure 1. Locations of the Rayong Bay and Map Ta Phut Port, Thailand.](image)

2. Study Area
The study area covers a long stretch of the east coast of Thailand from the Sattahip Peninsula on the west and Khao Laem Ya headland on the east as shown in Figure 1. The Rayong bay shoreline has approximately 60 km long located between latitude 12.58°N to 12.68°N and 100.95°E to 101.42°E. Geological features of the Rayong Bay include granitic rocks, terraces deposits and recent deposit, and the beach material mostly comprises of fine to medium sand with d50 of 0.1-0.6 mm [12]. The median grain size of gravels and shell-mixed gravel of about 0.1 mm was found farther of the coast (beyond 10 km from the shoreline)[15]. The sea bottom topography of the bay is generally gentle with the average gradient of about 1/600 [15]. Sea conditions are characterized by the tropical monsoon climate with two major seasons. The Southwest monsoon starting from May through September bring moderate to heavy rain and wind from the South and West, and the Southwest wind generates moderate waves on the Rayong coast with the heights of 1-2 m. The Northeast monsoon blows offshore from December to March producing small wave on along the coast [16]. Wave in this area is characterized by wind-induced waves. The predominant wave height is less than 1 m, and the wave heights more than 2 m is seldom with the prevailing wave period of 5-6 seconds [15]. Tides along the bay are diurnal and semi-diurnal depending on lunar age. The maximum tidal current speed range between 0.3-0.5 m/s and the direction of tidal current mainly is WNW-ESE [15]. The dominant southerly winds in the wet season with an average wind speed of 9.2 knots are much higher than the northerly wind speed in dry season [12]. Prior 1980s’, this area was used for mix farming with tree crops and orchard but the productivity was not very high [15].

Regarding the implementation of the Fifth Five-Year National Economic and Social Development Plan in Thailand started in October, 1981, the Eastern Seaboard project was developed as one of its main strategies to accelerate the region’s urban-industrial development and to deconcentrate the growth of the Bangkok Metropolitan region [15]. The MTP district was selected as a major base for an industrial port complex of petrochemical, fertilizer, and soda ash industries. To promote the location of heavy chemical industries in MTP, the Industrial Estate Authority of Thailand (IEAT), the MTP project executing agency, has conducted the construction of the MTP Port and the estate
development since 1989. The MTP Port was completed in 1992 (considered as Phase I). In response to the rapid increase of petrochemical industries located in Map Ta Phut, IEAT has expanded the Map Ta Phut Port (Phase II), which was completed in 1999, and facilities since 1998. Currently, the expansion of Map Ta Phut Port (Phase III) is under the process of Environmental Health Impact Assessment (EHIA) study.

3. Materials and Methods
Shoreline positions along the Rayong Bay during the past six decades were obtained from aerial photographs (1957, 1967, 1977, 1990, and 1996) and satellite imagery (2002, 2004, 2006, 2011, 2014, and 2016). Geographic Information System (ArcGIS) software version 10.4 developed by the Environmental Systems Research Institute (ESRI) was used to extract shoreline position from these data sources. All imagery data were geo-referenced into Universal Transverse Mercator (UTM) projection with the World Geodetic System 1983 (WGS1983) to eliminate distortion from aerial photographs and satellite imagery [17] [18], and then shoreline positions along the Rayong Bay coast were digitized for each of the 11 time intervals. Typically, shoreline is defined as the boundary between land and water, which represents the mean high water level [17] [18] [19]. Because Rayong Bay currently comprises of several different coast types, different proxies suggested by Zhang et al. [20] are used to define shoreline positions as shown in Table 1.

| Coast types  | Features     | Description of the position                  |
|--------------|--------------|---------------------------------------------|
| Rocky coast  | Cliff        | Base of cliff                               |
|              | Vegetation   | Seaward edge of the vegetation line         |
| Gravel coast | Beach ridge  | Seaward edge of the beach ridge              |
|              | Cliffs       | Line between the cliff and beach             |
| Muddy coast  | Vegetation   | Seaward edge of the vegetation              |
| Artificial coast | Dike     | Seaward edge of the dike top                |
|              | Port         | Boundary of the ports                       |

The rates of shoreline changes along the Rayong Bay were calculated using the extension of the ArcGIS, Digital Shoreline Analysis System (DSAS) version 4.4 developed by the United States Geological Survey (USGS) [21]. In DSAS, shoreline change can be analysed using the following steps: (1) define a baseline along the coast, (2) generate transects perpendicular to the baseline at user-defined spacing, (3) calculate rates of shoreline change for each time period corresponding to the baseline using either linear regression, endpoint rate, and weighted-linear regression rate. In this study, the baseline was created landward approximately 300 m from the shoreline. Totally 580 transects were generated along the Rayong Bay with 100 m spacing as depicted in Figure 2. The statistic of shoreline change rates along the Rayong Bay during the past 60 years was calculated with 90 percent of the confident interval. Shoreline change rates between pre- and post-project construction were compared to assess the impact of the mega coastal development project on the Rayong Bay.

4. Results and Discussion
The changes in the shoreline along the Rayong Bay during the period 1957-2017 were determined at each transect as depicted in Figure 3. Short-term rates of shoreline change were analyzed for three different time periods representing the average shoreline changes of the pre-port construction, between MTP Phase I and Phase II port construction, and the post-port (Phase II) construction. The details of shoreline changes as a result of the MTP Port development are discussed in the following subsections.

4.1. Shoreline Changes during the Period 1957-1990 (pre-Map Ta Phut Port development)
Based on the analysis of four shoreline positions of 1957, 1967, 1976, and 1990, it indicates that the Rayong Bay shoreline was mostly stable with the average rate of shoreline change less than 0.5 m/yr. Regarding to the variation of shoreline change in Figure 3 (the red solid line), the moderate rates of
shoreline accretion (1-5 m/y) were found locally near the mouths of major rivers and streams, and the maximum shoreline advance of about 4.5 m/y was found at the mouth of the Rayong River (between transects 402 and 417), which was the major river sediment supply to the Rayong Bay. Whereas, shoreline retreat was pronounced at the Khlot Stream (between transects 53 and 74) (Figure 3) with an average recession rate of -2.7 m/y as a result in shoreline adjustment to wave diffraction in the area. Over three decades prior the Map Ta Phut port development, the Rayong bay was relatively stable. The annual land growth and land loss rates between 1957 and 1990 were about 1.6 and 0.67 ha/y, and the pattern of deposition and erosion during this time period was mainly controlled by the riverine system and the coastal processes.

![Figure 2. Plot of transects used for the shoreline change evaluation along the Rayong Bay.](image)

### 4.2. Shoreline Changes during the Period 1990-2002 (during the Map Ta Phut Port development)

After the establishment of the MTP project in 1989, the IEAT has responsibility for developing and expanding the MTP Port and industrial complex. For the first stage of the development (Phase I), the Map Ta Phut Port, which comprised of a multipurpose berth and two liquid cargo berths (Figure 4) was completed in 1992. For the port facilities, a breakwater arranged in an approximately ESE direction was constructed on the west side of the port to protect the berths from SSW waves, and a reclaimed land with the 715 m wide and 1,720 m long was built on the east side (Figure 4). Based on shoreline change simulation studied by Japan International Corporation Agency (JICA) [15], the simulation results suggested that significant shoreline changes in the vicinity of the port would not occur after the Phase I’s port construction.

The comparison of the shorelines between 1990 and 1996 indicated that the existence of the MTP Port caused a significant shoreline accretion on the west and east sides adjacent to the port of 4.8 and 2.4 hectares, respectively. On the west side of the port, the beach growth occurred along the coastline between transect 242 and 249 (700 m) with the maximum extent of about 140 m. Nevertheless, the significant shoreline retreat averaging about 6.5 m (-1 m/y) was found along the 3 km of coastline from transects 220 to 241. Regarding the dimension and the orientation of the port, it acted as a large groin or jetty placing in the middle of the Rayong Bay and trapped the eastwardly longshore sediment transport resulting in accretion of the coast during the SW monsoon season. In contrast, the port prevented the longshore sediment moving eastwardly during the NE monsoon resulting in beach erosion with the average rate of -1 m/y along the upcoast of the deposition area. However, the effects of the MTP (Phase I) construction on the western coastline seemed to continue not beyond the Nam Rin Beach (transect 203, about 5 km away westward from the port) at which a bunch of submerged rocks was located. For the rest of the shoreline on the west side of the port, the rates of shoreline change insignificantly varied from place to place with the average rate of shoreline accretion and recession of about 1.7 m/y and -0.4 m/y, respectively.

On the east side of the port, the pattern of shoreline change in response to the MTP Port (Phase I) was similar to the west portion. The significant accretion of coast was found along 450 m of the shoreline adjacent to the port (between transects 277 and 282). Inversely to the west side, the growth of coast in
this section caused by the deposition of the littoral drift from the east impeded by the port. About 2 km long of shoreline erosion also was found next to the accretion area further to the mouth of Nam Hu Stream due to the deficit of longshore sediment transport between the SW and NE monsoons. However, the average rate of beach erosion along this segment was about -4 m/y, which was much higher than the erosion rate on the west side of the port (-1 m/y). Meanwhile, the significant accretion of the shoreline was noticed between transects 394 and 409 due to the construction of a jetty (400 m long) at the Rayong River mouth. The shoreline change rates of the remaining coastline was low (less than ±2 m/y on average) except a short section from transects 428 to 452, which was advancing seaward with the moderate rate of approximately 3 m/y as a result of the construction of the TPI port and gas pipeline between transects 436 and 445.

![Shoreline variation along the Rayong Bay during the period 1957-2016.](image)

Due to the rapid increase of enterprises located in the MTP Industrial Complex, IEAT expanded the facilities to serve the rapid growth of petrochemical plants, oil refineries, coal-fired power stations, and iron and steel facilities [12]. The expansion of the MTP Complex, considered as “Phase II”, included the construction of reclaimed land for 17 berths and its facilities. The reclaimed land of 1 km wide and 2.5 km long was constructed about 1.3 km from the shoreline and next to the east port in the project first phase as depicted in Figure 4. The construction of Phase II port was completed in 2002. In regard to the severe beach erosion after the Phase I port construction plus the expected beach erosion due to the expanded port in Phase II, series of coastal protection structures were used to mitigate the impacts of the construction of the port and its expansion on the eastern shoreline. As shown in Figure 4, the structures on the east side of the port consist of 7 straight groins with 25 m long and 65 m spacing, 22 detached breakwaters with 60 m long and 50 m spacing, and ten Y-shaped groins of 130 m long and 300 m spacing with a 50 m long breakwater placing between each pair of Y-shaped groin. Meanwhile, a straight groin (200 m long) and a T-shaped groin (300 m long) were installed on the west side of the port.

The Analysis of shoreline positions during the Phase I and II development of the Map Ta Phut Port indicated that, on the western shoreline of the port, moderate rates of shoreline accumulation were found near the mouths of natural streams such as Bang Phai, Phala, and Drainage Streams. While significant shoreline changes established near the coastal protection structures and local activities.
instance, the accretion of the coast was noticed between the Nung Stream (transect 209) and transect 219, where a shipwreck was situated (Figure 3). The construction of the T-shaped groin induced a shoreline accretion of 1.2 hectares between transects 232 and 236 with the maximum shoreline growth of about 100 m (Figure 3). Additionally, a groin with 100 m long placed at transect 246 induced shoreline accretion on the west side of the structure with the rate of about 3 m/y at both sides of the structure.

On the east side of the port, the jetty construction at the Rayong River’s inlet caused some continuous change of the adjacent shoreline. The typical pattern of accretion was found along 500 m of the western coastline of the jetty (between transects 403 and 408). As the severe erosion occurred between the port and the Rayong River mouth, the coastal protection structures mentioned above were installed as shown in Figure 4. It was found that the combination of a series of Y-shaped groins and breakwaters structures was placed along 2.7 km of shoreline on the west side of the jetty. The structures did not only interrupt longshore sediment but also protect the accreting beach from wave attack resulting in sediment accretion at both sides of each groin including salient developed behind each breakwater as shown in Figure 3. The maximum beach growth varied between 45 and 65 m.

![Figure 4. Development of the Map Ta Phut Phases I and II and coastal protection projects.](image)

Even though the amount of sediment accumulation was lower than the prediction in some cases, these structures were successful in building up the beaches. Typically, a groin system caused more downcoast erosion due to upcoast trap of sediment. Therefore, a series of twenty-two segmented breakwaters was installed parallel to the 2.5 km of the shoreline from transects 348 to 373 to stabilize the downcoast of the Y-shaped groins system. These breakwaters reduced wave energy and created a pocket beach or tombolo behind each segment with the area of tombolo ranging between 0.1 and 0.5 hectares. On one hand, this proved that the beach sediment was successfully retained along the protected shore. On the other hand, this meant that there was no sediment moving to the west of the breakwater system, and a significant down-drift starvation ensued. A series of seven straight short groins system with 23-27 m long was used to remedy this impact. However, significant shoreline response, if any could not be noticed downcoast of the straight groin system during this time period due to the ongoing land reclamation and road construction project along the shore between the Nam Hu Stream and Rayong River (transects 302-356).

On the west side of the Nam Hu Stream, as a significant shoreline erosion occurred due to the construction of the MTP Port (Phase I), the 1.7 km of the seawall was constructed to reclaim the land loss between transects 284 and Nam Hu mouth. Results from the shoreline analysis indicated that the construction of the seawall effectively stabilized the protected coastline, and about 3.5 hectares of the beach area was claimed. However, the non-protected coast between the edge of the seawall and the MTP port was reshaping to reach a new equilibrium as a result of coastal development activities in this area. Because the port acted as a very long groin trapping all the westerly longshore sediment transport, the updrift shoreline between transects 278 and 281 (350 m) rapidly grew with the maximum rate of about 16 m/y. Whereas, the downdrift shoreline of the transects 282-284 was experiencing ongoing erosion as a result of less sediment available. The maximum shoreline retreat rate of this cell was approximate -4 m/y. For the 17 km coastline from the Rayong River to the eastmost of the Rayong Bay,
most of the shoreline statistically remained stable. Only 13% of the shoreline in this section found near the TPI Port (transects 425-459) had significant accretion with the rate greater than 1 m/y due to land reclaimed for TPI port construction.

4.3. Shoreline changes since 2002 (post-Map Ta Phut Port (Phase II) construction).
Subsequent shoreline monitoring from 2002-2016 suggested that almost 30% of the Rayong total coastline experienced changes in shoreline positions in response to the MTP Phase II port construction and other coastal development activities. For instance, the 1.4 m/y of the maximum shoreline accretion rate was observed adjacent to the port on the west. While the shoreline accretion and recession continuously occurred on the non-protected area adjacent to the port on the east until 2014. The maximum rates of shoreline growth was 7.8 m/y, and the shoreline retreat was -2.3 m/y as shown in Figure 3 (black solid line). Due to the construction of coastal protection structures in 2002, the down-drift starvation occurred along the 4.5 km of the unprotected coast (from transects 302 to 347). More segment breakwaters, Y-shaped groins, and seawalls were added to stabilize that eroded portion in 2004. Although the dimension of segment breakwaters and Y-shaped groins of the additional coastal structures were similar to those constructed in 2002, only small salients were formed behind the new structures. The shoreline responded differently to the same kind of structures probably dominated by significant differences in coastal processes such as sediment supply, wave conditions, and beach characteristics.

After 2011, more than 98% of the total shoreline has statistically insignificant changes. As the average rate of shoreline changes for the whole Rayong Bay is currently less than 1 m/y, the Rayong Bay can be considered reaching a new dynamic equilibrium. The construction of the deep sea port with roughly 3.5 km wide, extending 4.0 km seaward directly affected the adjacent shoreline of 4.5 km on the west and of 12 km on the east (about 28% of the total shoreline). By using the appropriate engineering structures, the affected shoreline has recovered from the influence of the MTP Port construction within 2-6 years depending on the local coastal processes. This indicates that coastal engineering approach has successfully diminished the effect of the large deep sea port construction on the Rayong Bay shoreline.

As another expansion of Map Ta Phut Industrial Complex (Phase III) will be started in a very near future, the measures that will be used to mitigate the impact of Phase III port construction should be carefully designed. Moreover, the expected magnitude and time period of changes in coastal processes such as shoreline positions, wave conditions, and nearshore currents, in response to the port expansion should be informed to all stakeholders to minimize negative consequences and conflicts in order to be productive and successful over the long term.

5. Conclusion
The Map Ta Phut deep-sea port was constructed on the middle portion of the Rayong Bay as the major component of the Map Ta Phut Industrial Estate Project which has now been the successful and greatest base of petrochemical industries in Thailand. Historical shoreline change rates before the project development indicated that most of the Rayong Bay shoreline was in dynamic equilibrium with an average rate of less than ±0.5 m/y. After the completion of the Map Ta Phut Port (Phase I) construction in 1992, the significant shoreline accretion was found on the west and east sides adjacent to the port, and the shoreline retreat occurred along 3 km and 5 km of coastline on the west and east sides of the port, respectively. By the end of 2002, several types of coastal protection structures (seawalls, groins, and segment breakwaters, jetty) were built along the eroded areas affected by the Map Ta Phut (Phase I) port, and the 5 km of the eastern shoreline of the port was successfully reclaimed. Upon the expansion of the Map Ta Phut port (Phase II) in 2002, the shoreline recession on the west side of the port extended westward due to down-drift deficit as a result of the coastal protection scheme. More breakwaters and groins were added to mitigate the negative effects of adopted coastal protection structures. At present, the Map Ta Phut Port is 3.5 km wide and extends 4.0 km seaward, about 30% of the total shoreline of the Rayong Bay has been significantly disturbed by the port. However, engineering structures have successfully protected those affected areas, and more than 98% of total shoreline has now reached a new dynamic equilibrium since 2011.

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