J. Eng. Technol. Sci., Vol. 51, No. 3, 2019, 337-354

Alternative Designs for Semarang-Demak Coastal Dike and Toll Road

Andojo Wurjanto*, Julfikhsan Ahmad Mukhti & Shinta Ayuningtyas

Coastal Engineering Research Group, Ocean Engineering Program, Faculty of Civil and
Environmental Engineering, Institut Teknologi Bandung,
Jalan Ganesha 10, Bandung 40132, Indonesia
*E-mail: andojowurjanto@gmail.com

Abstract. Semarang city has been experiencing coastal flooding as a major problem. The flooding is inevitable due to the declining groundwater level as an impact of population growth and groundwater exploitation. The Indonesian Ministry of Public Works and Housing is currently planning to build the Semarang-Demak section of the Northern Java Coastal Tollway not only to fulfill traffic demand but also to fight coastal flooding. The purpose of this paper is to present alternative designs to support the plan and to provide recommendations based on design analyses as well as concerns from past design experiences. To the degree that is allowed by the available secondary data, reasonably detailed engineering calculations were performed to be able to present the dimensions of each alternative structure. The results of the structural and geotechnical analyses were obtained using suitable software for each type of analysis and the concerns based on past design experiences were investigated to find the most effective and efficient alternative.

Keywords: *coastal dike; flood defense; road; Semarang; subsidence.*

1 Introduction

Groundwater is being used extensively in Semarang city. Groundwater withdrawal has increased significantly from 1982 to 2002, respectively from 14 million m^3 in around 150 registered wells to 45 million m^3 in 1.200 registered wells [1]. It is presumed that groundwater exploitation is still accelerating due to the growth of the population, which increased by 16% between 2002 and 2015, as recorded by the Central Statistics Agency of Central Java (BPS) in Semarang [2]. This excessive groundwater withdrawal lowers the groundwater level, which leads to land subsidence. A subsidence rate of up to 8 cm/year in the coastal area of Semarang has been observed from January 2007 to January 2009, [3], which is about the same as the highest subsidence rate in Jakarta [4].

The most significant impact of land subsidence is the occurrence of inevitable periodic coastal flooding on the northern coast of Semarang. The most recent direct observation at the industrial area Terboyo, in May 2017, showed that the

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Received July 19th, 2018, 1st Revision January 7th, 2019, 2nd Revision March 15th, 2019, Accepted for publication April 1st, 2019.
Copyright ©2019 Published by ITB Journal Publisher, ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2019.51.3.3

road directly in front of the terminal was flooded in the daytime without rain. Moreover, residential areas such as Sriwulan Village were also impacted by coastal flooding once a month where the sea water level reaches the road level [5]. The annual coastal flooding, being a detriment to the residents as well as to industrial and economic interests, highly requires counteraction.

The Indonesian Ministry of Public Works and Housing intends to build the Semarang-Demak section of the Northern Java Coastal Tollway to secure inter-city logistic lines and connectivity. Initially, the toll road trace was planned to be built independently along the coastline, as shown in Figure 1. However, there was a change of plan in early 2017, to make the toll road also function as a coastal dike to prevent coastal flooding on the northern coast from Semarang to Demak [6]. The northern Semarang-Demak Toll Road will be 9.5 km long and the tollway-dike part will be 8 km long, as proposed by the Pemali-Juana Watershed Agency (*Balai Besar Wilayah Sungai Pemali Juana*) [7].

Figure 1 The trace plan of the Semarang-Demak tollway dike (redrawn from Balai Besar Wilayah Sungai Pemali Juana, 2017 [7]).

Engineering challenges are present in the design and building of this highway, especially since the structure is going to be built on a subsiding terrain with the prospect of active high-volume traffic. One valid approach to the design is to take examples from similar past problems, such as the Sedyatmo Toll Road. This toll road, which connects the city of Jakarta to Soekarno-Hatta Airport, had similar challenges as the Semarang-Demak Toll Road plan. Other examples are the development of the first phase of the Jakarta coastal dike project and the successful Afsluitdijk dike-causeway in the Netherlands, although the latter has required later improvement to keep the structure functioning properly, as discussed by Rijkswaterstaat [8].

This study aimed to develop three conceptual engineering design alternatives to the Semarang-Demak tollway-dike structure by taking lessons from several design experiences in the past using available data. Comparisons regarding the structural analysis and special concerns between the three alternatives are provided to select the most viable option. All design alternatives presented in this study use the trace plan proposed by the Indonesian Ministry of Public Works and Housing.

2 Methods

The method used in this study was to design a typical cross-section first, based on the environmental conditions and the dimension requirements given by the design standards for designing the geometry of toll roads published by Bina Marga [9] and by the Shore Protection Manual [10] for determining the structure's elevation and riprap dimensions. Structural and geotechnical analyses were then carried out to check the design integrity. Finally, the analysis result, as well as other non-analytical issues, were used as considerations in the design process.

3 Design Criteria

3.1 Environmental Data

3.1.1 Wave Height

Wave height data are required for determining the structure's crest elevation and the thickness of the armored layer in the riprap structure on which the toll road sits, which functions as an embankment. The common assumption that a structure sited at a water depth of d_s will be subject to breaking waves is applied if the condition is:

$$d_s \leq 1.3H \tag{1}$$

where H = design wave height.

In this study, the planned structure is located in a nearshore area, where the waves should be broken already by the time they reach the dike since the water around the dike trace is only about 2 m deep [11]. Following Eq. (1), the design wave height was taken as 2 m.

3.1.2 Tidal Data

Tidal data were obtained by forecasting one year based on the water level data for the Semarang North Coast in 2017 retrieved from the Naval Hydrography and Oceanography Center (Pushidrosal) [12]. The tidal elevation data obtained from the forecast using the ERGTide software are shown in Table 1, from which a tidal range of 87 cm was determined.

Table 1 Tidal elevation data obtained from forecasting.

Elevation	Elevation (software output)	Elevation from MSL
Highest water spring (HWS)	98.03 cm	43.23 cm
Mean high water spring (MHWS)	90.77 cm	35.98 cm
Mean high water level (MHWL)	72.44 cm	17.64 cm
Mean sea level (MSL)	54.80 cm	0.00 cm
Mean low water level (MLWL)	36.01 cm	-18.79 cm
Mean low water spring (MLWS)	18.61 cm	-36.19 cm
Lowest water spring (LWS)	11.52 cm	-43.28 cm

3.2 Geotechnical Data

Geotechnical data obtained from soil investigations conducted in the Silandak River estuary and Kendal Port [13] were used, with the result shown in Table 2. It was found that to a depth of 20 m, the soils are mostly soft, in the form of loose sand, soft clay and very soft clay. Hard soil was found at the depth of 20 m in the form of stiff clay to a depth of 33 m, and very stiff clay from 33 m to 75 m.

Table 2 Soil characteristics (processed from data retrieved from the Public Works Department of Republic of Indonesia [13]).

Layer	Depth (m)	$\overline{\mathrm{N-SPT}}$	Soil Category	γ $(\mathrm{kN/m^3})$	Cu $(\mathrm{kN/m^2})$	φ (°)	k $(\mathrm{kN/m^3})$
1	0-5	11	Loose sand	16	-	27	4000
2	5-10	5	Soft clay	17	40	-	18000
3	10-20	3	Very soft clay	16.5	27	-	3500
4	20-33	16	Stiff clay	17.5	100	-	140000
5	33-75	25	Very stiff clay	18	200	-	230000

Notations:
γ = soil density (kN/m^3)
Cu = soil cohesion (kN/m^2)
φ = angle of repose (^{o})
k = soil modulus (kN/m^3)

3.3 Sea Level Rise

According to the Indonesian Ministry of Ocean and Fishery, the average sea level rise in the Semarang coastal area is 6 mm/year [14]. This value is required for considering the structure's crest elevation since the structure is expected not to be submerged and not to succumb to a rise of the sea level.

3.4 Structural Dimensions

3.4.1 Crest Elevation

The crest elevation of a coastal structure is the sum of several components and is calculated as follows:

$$h = SWL + R + F + LS + SLR \tag{2}$$

where SWL (m) is still water level, R (m) is run-up height, F (m) is freeboard, LS (m) is land subsidence, and SLR (m) is sea level rise. In a vertical wall, the run-up height can be considered at $R = 0.5H_s$, where H_s is the design wave height.

The still water level is considered as the tidal range, or the difference between the HWS elevation and the LWS elevation as mentioned in Sub-section 3.1.2. The run-up height was calculated based on the breaking design wave height as mentioned in Sub-section 3.1.1. The freeboard value in this calculation was assumed to be 0.55, while the land subsidence and the sea level rise, stated respectively in Section 1 and Sub-section 3.3, were calculated for 30 years of occurrence.

Referring to Eq. (2), the structure's crest elevation was calculated as follows:

$$h = (0.87 + 0.5 \cdot 2 + 0.55 + 2.4 + 0.18)\ \text{m} = \mathbf{+5\ mLLWL}$$

With this crest elevation, it is expected that the structure will last at least 30 years. Since the dike is constructed with earth fill material, it can be refilled to compensate for the loss of crest height due to natural land subsidence as well as human activities such as passing vehicles.

3.4.2 Toll Road Width

The structure's crest width was determined by considering its function as a toll road. According to Bina Marga [9], the toll road will consist of several parts with a certain minimum width. The preliminary design of the toll road is intended for 2 lanes in each direction. The width consideration of each part is shown in Table 3.

Table 3 Width consideration of each part of Semarang-Demak toll road (Bina Marga [9]).

Toll Road Part	Information
Median	Minimum width of 5.5 m for intercity toll roads (measured from the inner line of the travel lane)
Inner shoulder	Minimum width of 1.5 m for intercity toll roads on which a maximum vehicle velocity of 120 km/h works
Travel lane	Ideal width of 3.75 m for one lane of intercity toll roads on which a maximum vehicle velocity of 120 km/h works
Outer shoulder	Ideal width of 3.5 m for intercity toll roads on which a maximum vehicle velocity of 120 km/h works
Clearance	Assumed length

4 Design Alternatives

4.1 Design Alternative 1

The first alternative (Design Alternative 1) is to build the toll road on an embankment that sits on the subsiding soil. This design is adapted from the concept of the Afsluitdijk dike-causeway in the Netherlands, which separates the Wadden Sea and the IJsselmeer artificial lake. The Afsluitdijk has successfully protected the country from the sea for more than 80 years, although a plan to reinforce the Afsluitdijk in 2018 is currently under works due to sea level rise and deterioration of the dike’s water discharge [8]. The construction of the dike consists of a till (boulder clay) on the side facing the sea [15], which grants the dike impermeability. On the seaside, riprap stones are arranged as the outer cladding of the structure, with the toe designed to avoid scour. The toll road cross-sectional view of this alternative is shown in Figure 2(a). The complete cross-sectional view of Design Alternative 1 is shown in Figure 3.

4.2 Design Alternative 2

The second alternative (Design Alternative 2) is to build separate-but-integrated structures to prevent coastal flooding and to have the highway function in the form of pavement that sits on an embankment designed above sea level. This structure is protected by another structure, a nearby coastal dike. This coupled design is adapted from the National Capital Integrated Coastal Development (NCICD) project [16]. In the NCICD design, the coastal dike is constructed as an integration of piles that form a wall facing the sea. A landfill is provided at the back of the piles to make the coastal dike watertight. Based on careful observation of the development of the Jakarta coastal dike, this study recommends the dike structure to be made of steel piles instead of concrete piles since steel piles are easier to work on and maintain. The toll road cross-sectional view of this alternative is shown in Figure 2(a). The complete cross-sectional view of Design Alternative 2 is shown in Figure 4(a).

4.3 Design Alternative 3

The third alternative (Design Alternative 3) also presents separate-but-integrated structures, with a coastal dike that is similar to that in Design Alternative 2. However, in this alternative the highway is constructed as a deck-on-pile structure. Such a highway structure has been applied in the additional elevated lanes of the Sedyatmo Toll Road, both on its northern and southern sides to avoid the risk of flooding. The upper structure, however, consists of concrete slabs, which are common for highways in Indonesia. The toll road cross-sectional view of this alternative is shown in Figure 2(b). The complete cross-sectional view of Design Alternative 3 is shown in Figure 4(b).

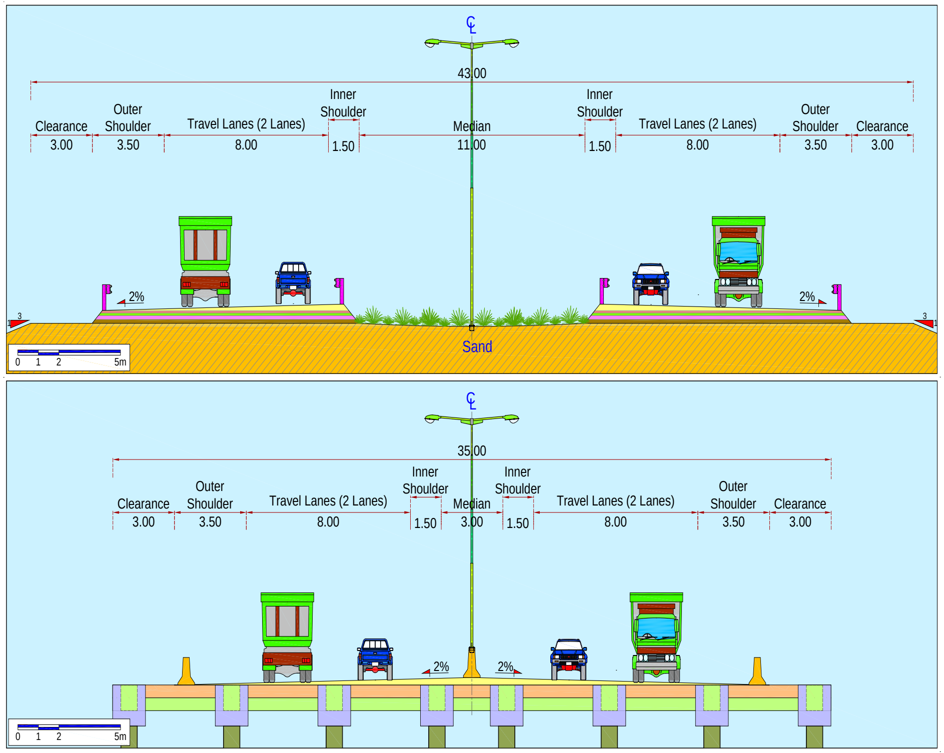


Figure 2 Cross-sectional views of the Semarang-Demak Toll Road for (a) Design Alternative 1 and 2, and (b) Design Alternative 3.

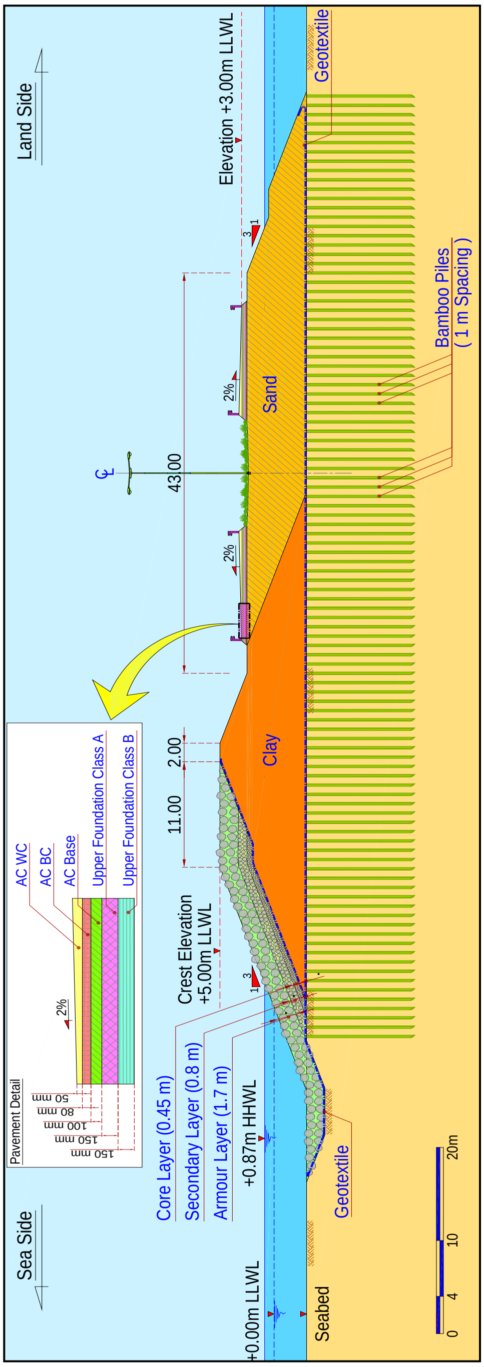


Figure 3 Design Alternative 1 of the Semarang-Demak dike-causeway.

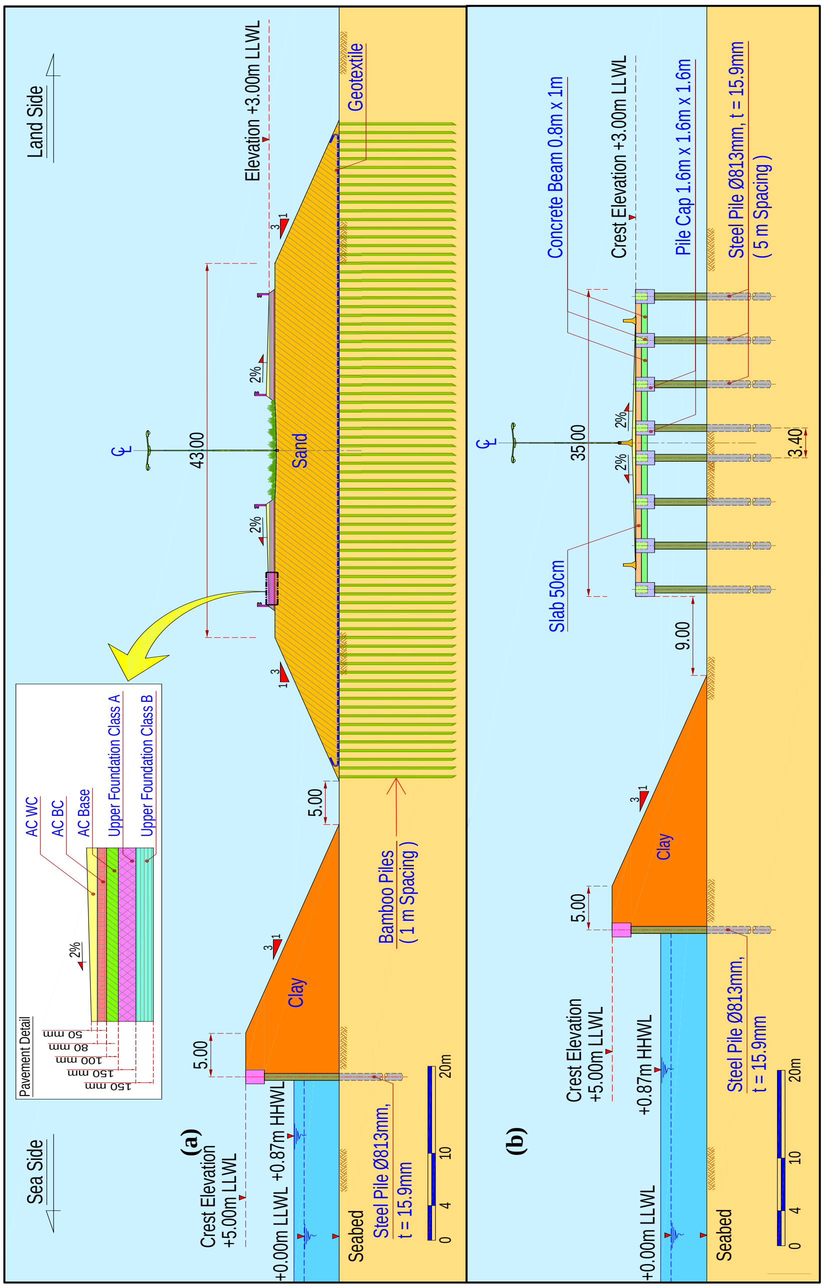


Figure 4 Design of (a) Alternative 2 and (b) Alternative 3 of the Semarang-Demak dike-causeway.

5 Analysis

5.1 Structural Analysis

The structural strength of the tollway-dike structure in Design Alternative 1 and the tollway structure in Design Alternative 2 was examined by using geotechnical analysis software with soil characteristics, external loads, and soil geometry as input parameters. The strength of each structure was determined by investigating the collapse pattern, safety factor, inner forces, and displacement output parameters.

Macro-structural analysis software was used for modeling the deck-on-pile structure functioning as the highway in Design Alternative 3. The software required the structure's material specification, component dimensions, and external loads as input parameters. The strength of the structure was examined by studying the strength ratio and the displacement of the structure.

The highway structural model in Design Alternative 3 has three types of elements: node, frame, and area, where the frame elements required exactly two nodes to be set and the area elements requires at least three nodes to be set. The beam of the deck was modeled as horizontally interconnected frame elements. The deck plates were modeled as area elements that are attached to every interconnection of the beams. The piles were modeled as frame elements attached from the beam/plate interconnections to the depth of the fixity point. The pile caps, however, were not modeled as elements but instead as superimposed dead load.

Micro-structural analysis software was used to check the structural integrity of a single pile representing the integrated piles in Design Alternative 2 and 3. This software has the advantage of giving a clearer output of stress and displacement on a single pile compared to macro-structural analysis software, which is critical to design structures subject to earth pressure. The pile foundation of the dike has the same size as the piles in the deck-on-pile structure.

Figure 5 shows the structural model of the deck-on-pile structure in Design Alternative 3. The result shows the maximum stress ratio and the deformation of the steel piles, which ensures that the given allowable values are not exceeded. Figure 6 shows the component model of a single pile of the dike in Design Alternative 2 and 3. Based on the analysis results, this structure is also safe in terms of stress ratio and deformation is considered insignificant.

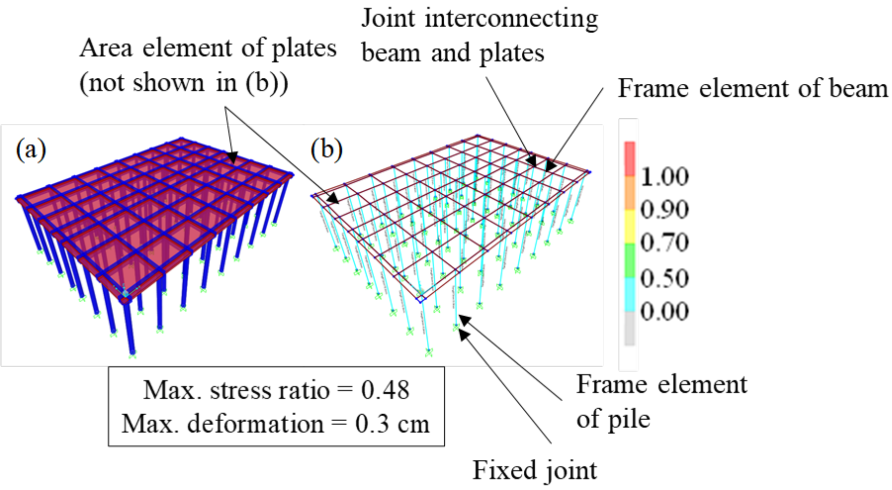


Figure 5 Structural analysis model of deck-on-pile structure in Design Alternative 3 (a), and the result diagram of its strength ratio (b).

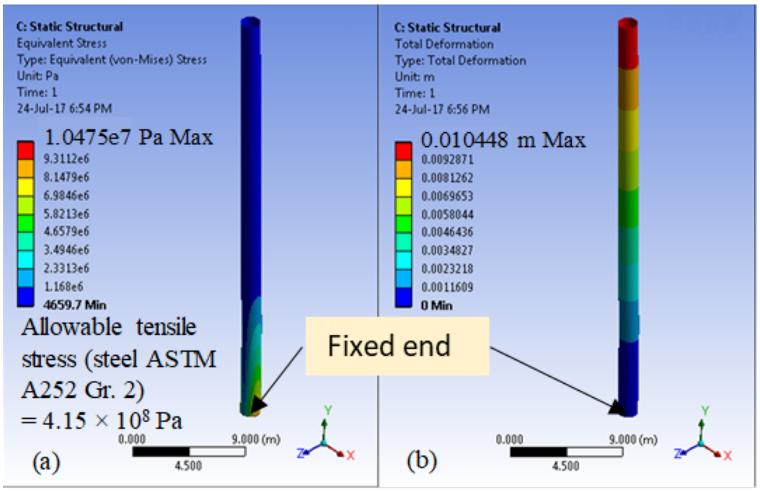


Figure 6 Structural component model of the dike's pile structure in Design Alternative 2 and 3, showing the stress (a) and the deformation result (b).

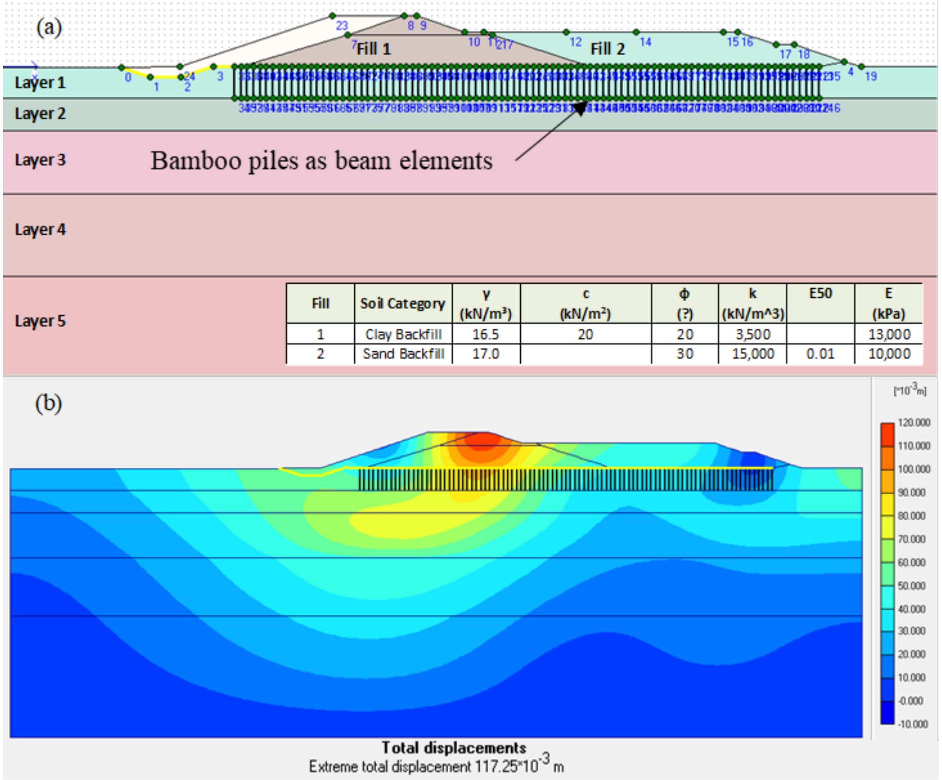
5.2 Geotechnical Analysis

A geotechnical analysis was necessary to examine the reliability of the design from a geotechnical point of view. A model was made for all design alternatives by using geotechnical software. The model of Design Alternative 1 includes the entire backfill in the cross-section, while the models of Design Alternative 2 and 3 only include the dike, since this is the main concern for flood prevention.

The embedded bamboo pile row in Design Alternative 1 in Figure 7 was modeled as beam elements, where the element meshing can ‘flow through’ the pile row. However, the dike pile in Design Alternative 2 and 3 in Figure 8 is a fixed-plate element, since the ocean-facing side of the dike consists of tightly placed piles.

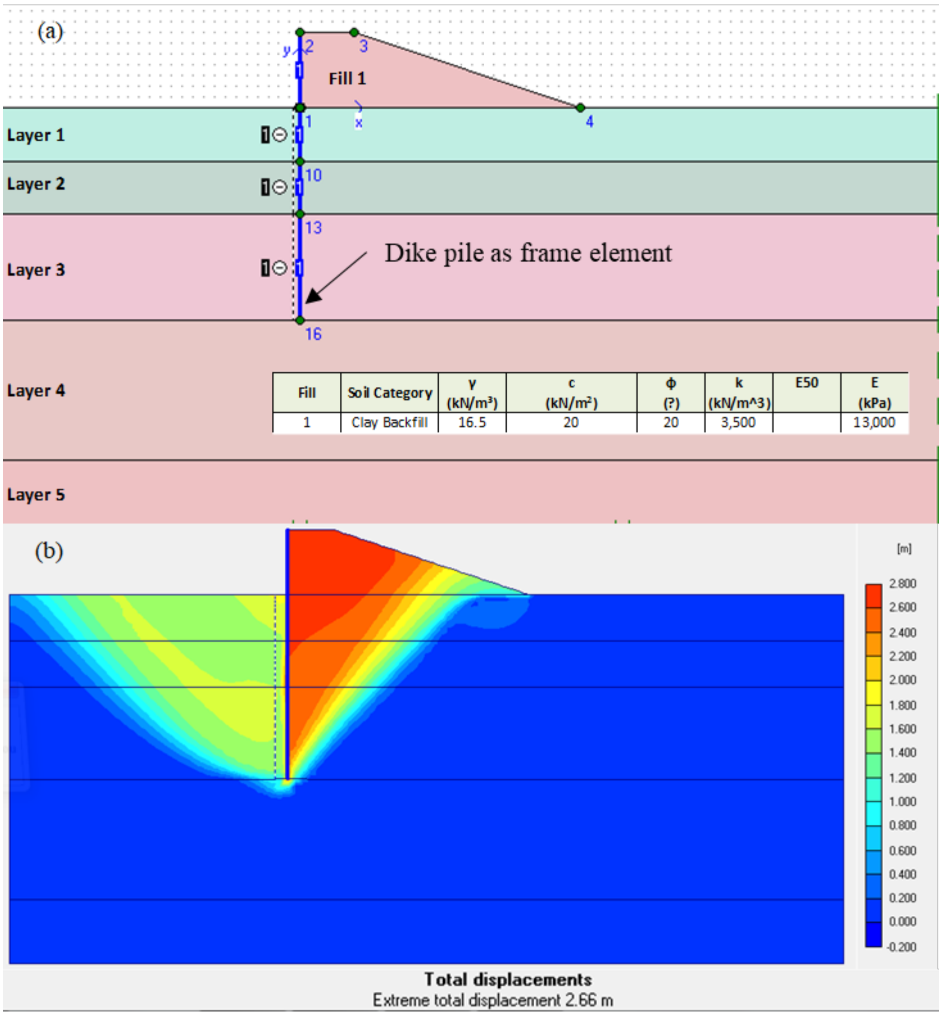
The result of the safety factor (SF) from the analysis of Design Alternative 1 is below 1.00 in failure condition, where the stress rate of the soil reaches its yield strength, which means that the fill is not stable despite a low extreme total displacement of 0.12 m.

The analysis of Design Alternative 2 and 3 shows a higher SF (2.48) and also a higher displacement (2.6 m) in failure condition. However, for condition SF = 1, the displacement is significantly lower (0.13 m). Figures 7 and 8 show the geotechnical analysis model and result for each design alternative.



Fill	Soil Category	γ (kN/m³)	c (kN/m²)	ϕ (?)	k (kN/m^3)	E50	E (kPa)
1	Clay Backfill	16.5	20	20	3,500		13,000
2	Sand Backfill	17.0		30	15,000	0.01	10,000

Figure 7 Geotechnical software (a) model for Design Alternative 1 and its (b) displacement analysis result.



Fill	Soil Category	γ (kN/m³)	c (kN/m²)	ϕ (?)	k (kN/m^3)	E50	E (kPa)
1	Clay Backfill	16.5	20	20	3,500		13,000

Figure 8 Geotechnical software (a) model for Design Alternative 2 and 3 and their (b) displacement analysis result.

5.3 Dike Armor Design Analysis

The dike armor dimensions were calculated using Hudson’s formula. Based on the calculation, the minimum armor layer thickness is 1.4 m, where the design uses 1.7 m for additional safety.

6 Discussion

6.1 Analysis Results

Based on the structural analysis result for Design Alternative 2 and 3, it can be ensured that all design alternatives are reliable, since the stress ratios are significantly lower than the allowable stress. The structural displacement, at a maximum of 1 cm, is also very low. Backed by a correct maintenance method, such as the installation of cathodic protection on the steel piles, the structural integrity should be able to be maintained for the structure's service lifetime, except when subjected to extreme or unusual conditions (i.e. ramming by a ship or loaded by heavy machinery).

In terms of geotechnical aspects, however, was shown that the fill presented in Design Alternative 1 and 2 may not be compatible with the existing soil. Further geotechnical investigation and soil improvement are required to settle the fill and increase its stability.

6.2 General Concerns

This study, as described in Section 1, does not propose a new trace plan for the design of the tollway-dike structure. Regardless of the alternatives, there are concerns with the social and environmental impacts.

Moving the tollway-dike trace from the inner part of the Semarang-Demak northern coast towards the ocean will minimize the amount of land acquisition. At the time this study was conducted, there was no official confirmation which pre-owned lands will be acquired to build the tollway-dike, but based on the given trace, the work will take place between the Terboyo area at the western end (Semarang) and Sriwulan at the eastern end (Demak). Based on field observations by the authors at those two locations, these areas are relatively lowly populated, as shown in Figure 9. Furthermore, these areas are also already regularly inundated, which could make the relocation socially less impactful for the existing residents.

At the time that this study was conducted, there was no official public information regarding the mitigation of environmental impacts that may be caused by the construction of the tollway-dike. However, based on the report provided by the Pemali Juana Watershed Agency [17], several efforts using natural and artificial materials have been carried out before 2016, including mangrove rehabilitation, construction of a 'coastal belt' using concrete cylinders, and detached breakwaters. This implies that coastal flooding and abrasion have already had a huge impact on the residents and the construction of tollway-dike itself is a more comprehensive effort to prevent the northern part of Semarang-Demak from being flooded.

Figure 9 The areas at both ends of the tollway-dike, which are not highly populated.

Also, the shallow water areas that are currently right behind the proposed tollway-dike plan are going to be replaced by retention pools. There is currently no public information regarding where the public activities that currently use the shallow water areas around the tollway-dike trace – such as shrimp farming – will be relocated. The feasible way is to relocate the farms outside of the tollway-dike so the farmers can still get the saltwater intake required for farming.

There is also currently no public information available regarding how the earth filling may impact aquatic life. However, since all shallow water activities will be most likely moved to the sea in front of the tollway-dike, the economic impact regarding the reclamation is expected to be minimalized.

6.3 Alternative-Specific Concerns

The implementation of each design alternative includes several concerns that have to be taken into consideration. In Design Alternative 1, loads working on the embankment increase the stress that compresses the soil layers and inflicts soil settlement. The soil settlement is also worsened by the land subsidence occurring on the ground due to the lowering of the groundwater level. Thus, Design Alternative 1 requires periodic overlaying of the embankment, which would prove, from the lessons learned, to be taxing in terms of cost and highly disruptive to the function of the tollway. If the subsidence is assumed to be doubled due to passing vehicles plus the large mass of the earth fill itself, the structure may lose up to 2.5 m of crest elevation within 15 years. However, Design Alternative 1 offers the concept of a single structure that has a ‘two-in-one’ function.

In Design Alternative 2, the concern is water leakage due to unexpected holes or cracking that may occur in the surface of the dike’s wall. This is even riskier if the holes or crack points cannot be detected exactly. The embankment on which the toll road sits is allowed to subside over time without any urgency of overlaying, because it is protected by a separate coastal dike. Nevertheless, in the future, it may be difficult to expand the toll road width, especially if the settlement of the soil is uneven across the embankment.

In Design Alternative 3, the deck-on-pile structure makes the rate of soil settlement lower than that in Design Alternative 1. Piles are driven up to a depth where hard soil is found, which makes settlement virtually inexistent for the toll road. Moreover, it is easier to expand the toll road width in the future when necessary. Since this alternative uses a coastal dike design that is identical to the one used in Design Alternative 2, the concern regarding potential leakage of the dike is the same as explained in the previous paragraph.

7 Conclusion

A reasonably detailed structural and geotechnical analysis has been done on all three alternatives based on the standards used in this study to the extent allowed by the available secondary data. Design Alternative 3 is preferable over to the other two alternatives, since it is the least prone to land subsidence, which is a concern with the massive earth fill presented in Design Alternative 1 and 2. However, Design Alternative 3 may have a relatively high capital cost compared to Design Alternative 1 and 2, although in the long run, the cost of maintenance, the need for soil refilling due to subsidence, and road crack maintenance caused by uneven subsidence may outweigh its higher capital cost.

This study could be further improved by including more accurate environmental data, especially geotechnical boring logs, since the data used in this study were relatively very conservative in terms of soil bearing capacity. Using better geotechnical data would also mean that subsidence of the fills presented in Design Alternative 1 and 2 over time can also be modeled properly. Ultimately, the benefits and concerns of each alternative can be compared more comprehensively using an economic analysis. In the current state, however, it is not required to model the subsidence analysis since the fill stability failed due to the high burden load.

Acknowledgements

We would like to thank the Pemali-Juana Watershed Agency for providing the trace plan data that was used as one of the considerations in the design of the alternatives presented in this study.

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