The comparison of empirical and finite element methods to evaluate soil foundation capacities for coastal dike

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Abstract. There are over 6,300km of coastlines in the North Maluku province of Indonesia due to tidal waves which originate from the pacific ocean. The waves deposit finely loosed materials and light soil formations on coastlines, therefore causing abrasion. A common example occurred in Toseh, Tidore, and Archipelago districts. Moreover, the local residence has been faced with this challenge for up to thirty years. For this reason, deliberations to construct a dike became significant, although, the soil properties are vulnerable. This reasearch, therefore, compares the empirical calculation to the finite element method (FEM) to ascertain soil foundation capacities. The results showed the safety factor, Fs, for dike height, H_d, of 3.5 m and width bottom, B_1, of 12.5m appeared below 2.0 for soil friction φ_s of 10~ 15°, while estimates above 2.0 depicts soil friction φ_s of 20°. Furthermore, the soil stresses beneath the dike were determined empirically at q_{max} of 5.97 t/m² and σ_y of 4.57 t/m², while FEM evaluated the deformation elastic at 12.5 cm.

1. Introduction

North Maluku is a province in Indonesia characterized by extensive coastlines where over 40% suffered abrasion due to natural disasters [1]. This is triggered by the existence of soft clay, and/or loose sand deposits. However, several structures, including residences, roads, public offices etc, owned by government and private entities are situated in this district, although, these properties are constantly threatened by unfavorable wave action.

As one of the counter measures to prevent the natural disaster, tall dike have been erected. These were built without any physical significance to geotechnical standards. This study reports the comparison of the calculation method in the design of coastal dike on silty sand soil. Typical cases include Toseho village, Tidore, and Archipelago district in Halmahera Islands, North Maluku.

These local communities are known to settle in traditional houses along coastlines built with conventional construction methods for 40 years. Figure 1 revealed these locations, in recent development, no longer provide safe habitation due to high risk of wave disturbance.
a) Recently land situation of the local houses  
b) Sand material views at the ground surface

Figure 1. Photo recently situation of the local residential at Toseho coastline (Photographer Suyuti, 24.08.2019).

However, the unfortunate breakdown of these residences was attributed to coastal abrasion as only trees were used as protection mechanism. In addition, over 15 families are known to currently reside on Toseho coastline and figure 2 captures the present condition.

a) Houses before collapsing  
b) Houses after damaged by sea waves

Figure 2. Photo recently situation of the local residential at Toseho coastline (Photographer Suyuti, 24.08.2019).

Figure 2 also shows the traditional semi-permanent houses built with materials such as bamboo used as reinforcement for the basic wall, sand for wall, wood for buttress, midrib of sugar palm for wall, etc.

For a long time, the people settled for conventional methods of coastal protection such as planting trees, coral stones construction etc [2], hence, the need to undertake modern dike construction. This study, therefore, aims to provide design calculations for this purpose.

2. Methodology of Research
The empirical and FEM approach compares the nature of wave forces on the dike. In addition, the required stability criterion of soil foundation is calculated by following flow chart (figure 3).
2.1. *Measure tidal waves*

Three points (A, B and C) were marked on the coastline at a length of 483 m at Toseho to measure the tidal waves. Furthermore, by using global positioning system (GPS), the coordinate point surveyed on April 21st, 2020 generated 0°20’57.91"U and 127°39’17.30”T. The coordinates using Google Earth application are shown in Figure 4.

![Figure 3. Flow chart of design calculation for dike.](image)

Figure 4. Photo of three points of the coastline situation at Toseho Village (Photographer Zhafirah, 21.04.2020).

Figure 4 also indicates the various wave elevations obtained 1.05 ~ 2.0 meters at a length of 20 m on the cross section [2].
2.2. Soil layer for foundation
The soil layer was investigated by a simple method to express the parameters for the foundation, e.g. cohesion (c, t/m²), internal friction (\(\phi, ^{\circ}\)), and unit weight of the saturated soil (\(\gamma_{sat}, t/m^3\)). Meanwhile, the surface layer was tested by plugging a hole on the ground surface.

2.3. Design and dimensions of the dike
The design was prepared without any reinforcement using dimensions such as width at top (\(B_0, m\)), height (\(H_d, m\)), width at bottom (\(B_b, m\)), gradient slope at the front side (\(n_1\)), and gradient slope behind the structure (\(n_2\)). However, the dike was constructed with a foundation depth (\(D_f, m\)), and design height in respect to design water level of waves (DWL is High water level added by global warming) (figure 5) [3].

![Figure 5. The prototype of dike on the subsoil use for coastal.](image)

Figure 5 shows that width of the bottom \(B_b\) used to make simplified for calculation, it is based on assumption footing of dike as rigid footing foundation with depth \(D_f\) (m).

3. Fundamental Theory
The required stability criterion was prepared with allowable bearing capacity of soil foundation and the vertical loading pressure provided as follows:

3.1. Empirical Equations and formulas
The factor of the vertical loading pressure of the dike to allowable bearing capacity of soil \(F_s\) is written as: [4]

\[
F_s = \frac{q_m}{p_d} > 2.0
\]

(1)

The foundation pressure beneath the coastal dike construction (without waves force) \(p_d\) (t/m²) is calculated by:

\[
p_d = \gamma_d H_d
\]

(2)

By simplifying, the classical theory of Terzaghi and Peck (1948) may be used to predict ultimate bearing capacity of soil \(q_m\) (t/m²) [5].

\[
q_m = cN_c + qN_q + \frac{1}{2} B_b \gamma_s N_s
\]

(3)
The allowable bearing capacity of soil $q_{us}$ (t/m$^2$) is calculated by:

$$q_{us} = \frac{q}{F_s}$$

(4)

where $c$ = the cohesion of soil (t/m$^2$), $q$ = the pressure at ground surface (t/m$^2$) ($q = \gamma_{sat} \times D_s$), $D_t$ = foundation depth (m), $\gamma'$ = the effective unit weight of soil (t/m$^3$) ($\gamma' = \gamma_{sat} - \gamma_w$), $\gamma_{sat}$ = the unit weight of saturated soil (t/m$^3$), $\gamma_w$ = the unit weight of water (t/m$^3$), $N_c$, $N_q$, $N_\gamma$ are factor of bearing capacity respected to the internal friction of soil ($\phi'$).

This section investigates the internal friction of the soil $q_e$ ($^0$) by a simple method to observe the surface density condition.

Load stress of the dike construction on the soil ground surface $q_{\text{max}}$ (t/m$^2$) due to wave forces is calculated by: [6]

$$q_{\text{max}} = \frac{\sum V}{B_b} \times \left(1 \pm \frac{6e}{B_b}\right)$$

(5)

where $\sum V$ = total of vertical load (ton), $B_b$ = width bottom of the dike (m)

The eccentricity of dike construction $e$ (m) due to the moment of coastal wave forces is predicted by: [6]

$$e = \frac{B_b}{2} - \frac{\left(\sum V \times (\sum MV - \sum MH)\right)}{6} < \frac{B_b}{6}$$

(6)

where $\sum MV$ = total moments of dike vertical load (t.m), $\sum MH$ = total moments of wave horizontal load (t.m), $\sum V$ = total vertical load (ton).

3.2. Finite Element Method-2D

Finite Element Method (FEM) is applied by following the plane strain model in order to compare empirical calculation. The global relation between force ($\mathbf{F}$, kN), stiffness of materials ($\mathbf{K}$, kN/m$^2$), and displacement ($\mathbf{U}$, m), is shown by equation [7]

$$\{\mathbf{F}\} = [\mathbf{K}] \{\mathbf{U}\}$$

(7)

In the soil parameter using Mohr-Coulomb material model for FEM-2D simulation, the relation between Young’s Modulus ($E_s$, kN/m$^2$), shear modulus ($G_{\text{ref}}$, kN/m$^2$), Eodometer modulus ($E_{\text{eod}}$, kN/m$^2$), and Poisson’s ratio of soil ($\nu$) are written as [8],

$$G_{\text{ref}} = \frac{E_s}{2(1 + \nu)}$$

$$E_{\text{eod}} = \frac{(1 - \nu)E_s}{(1 - 2\nu)(1 + \nu)}$$

(8)

(9)

3.2.1. Making geometry model

The geometry of dike on the ground estimated to produce the FEM-2D simulations of the coastal dike on a silty sand layer. Geometry model is made coordinates of points (x, y) as shown in figure 6.
Figure 6. Modeling geometry of dike on the ground for FEM-2D.

3.2.2. Soil parameters of material model

Soil parameters and dike simulations were provided to calculate the stability criterion. The soil properties at the ground are roughly predicted that based on field investigation. It is found loose to medium layers of silty sand [2, 4]. The results of input parameters of soil and dike are listed in table 1 and table 2, respectively.

Table 1. Input soil parameter of soil [2, 4, 9].

| Soil layer | Loose layer | Medium layer | Hard layer |
|------------|-------------|--------------|------------|
| Depth (m)  | 0 ~ 12.5    | 12.5 ~ 20    | 20 ~ 50    |
| Material type | Drained   | Drained      | Drained    |
| Parameters of soil: Unit |             |              |            |
| Unsaturated ($\gamma_{unsat}$) (kN/m$^3$) | 12.5 | 15.0 | 18.0 |
| Saturated ($\gamma_{sat}$) (kN/m$^3$) | 17.5 | 19.0 | 21.0 |
| Permeability $k_x$ (m/day) | 1.0 | 2 x 10$^2$ | 2 x 10$^4$ |
| Permeability $k_y$ (m/day) | 1.0 | 2 x 10$^2$ | 2 x 10$^4$ |
| Cohesion (c) (kN/m$^2$) | 1.0 | 1 | 1 |
| Internal friction $\phi$ (°) | 20 | 25 | 30 |
| Young Modulus $E_s$ (kN/m$^2$) | 1.23 x 10$^4$ | 4.5 x 10$^4$ | 9.8 x 10$^4$ |
| Poisson’s ratio $\nu_s$ | 0.35 | 0.3 | 0.3 |
| Dilantancy $\psi$ (°) | 0 | 0 | 0 |
| $G_{ref}$ (kN/m$^2$) | 4.56 x 10$^4$ | 1.73 x 10$^4$ | 3.76 x 10$^4$ |
| $E_{oed}$ (kN/m$^2$) | 1.974 X 10$^4$ | 6.5 x 10$^4$ | 1.32 x 10$^5$ |
| Velocity $v_s$ (m/s) | 59.76 | 106.3 | 143.3 |
| Velocity $v_p$ (m/s) | 124.4 | 198.9 | 268 |
Table 2. Input soil parameter of dike [2, 9].

| Material type          | Drained |
|------------------------|---------|
| Parameters of dike:    |         |
| Unsaturated ($\gamma_{\text{unsat}}$) | (kN/m$^3$) | 19.0  |
| Saturated ($\gamma_{\text{sat}}$)      | (kN/m$^3$) | 22.0  |
| Permeability $k_x$     | (m/day)  | 100   |
| Permeability $k_y$     | (m/day)  | 100   |
| Cohesion ($c_d$)       | (kN/m$^2$) | 1     |
| Internal friction $\varphi_d$ | (˚)     | 40    |
| Young Modulus $E_d$ [9] | (kN/m$^2$) | 1.2 x 10$^5$ |
| Poisson’s ratio $\nu_d$ | -       | 0.3   |
| Dilantancy $\psi$     | (˚)     | 10    |
| $G_{\text{ref}}$      | (kN/m$^2$) | 4.6 x 10$^4$ |
| $E_{\text{ned}}$      | (kN/m$^2$) | 1.6 X 10$^5$ |
| Velocity $v_s$        | m/s     | 154.3 |
| Velocity $v_p$        | m/s     | 288.7 |

The soil and dike parameters are modeled in Mohr-Coulomb and drained material type. It is setting up as materials elasto plastic in calculation for stability and settlement criteria.

3.2.3. The application program of FEM-2D

The FEM application was employed commercial software to calculate the stress and displacement at every point. Meanwhile, the gradient slopes $n_1$ and $n_2$ were placed at the ocean side and behind the dike, respectively. Furthermore, dimension geometry was applied based on design results to implement empirical calculation.

4. Results and Discussions

Based on simple tests in field, soil parameters for the calculation of bearing capacity were assumed such as internal soil friction $\varphi_s$ of 10 ~ 20°, unit weight $\gamma_{\text{sat}} = 17.5$ kN/m$^3$[10]. It is shown in Figure 7.

Figure 7. Schematics of the overturning moment due to sea waves.

Figure 7 shows the dimensions of the structure were used by height $H_d$ of 3.5 m, width the top $B_0$ of 2.0 m, $n_1 = 2$, $n_2 = 1$, bottom $B_1$ of 12.5 m.
The calculation results of factor of safety $F_s$ are listed in Table 3.

| Soil internal friction $\varphi_s$ (°) | Bearing capacity $q_{us}$ (t/m$^2$) | Factor of safety $F_s$ | Remark |
|--------------------------------------|--------------------------------------|------------------------|--------|
| 10°                                  | 8.3                                  | 0.95 $<$ 2.0           | No. Safe |
| 15°                                  | 16.2                                 | 1.84 $<$ 2.0           | No. Safe |
| 20°                                  | 31.2                                 | 3.56 $>$ 2.0           | Safe    |

The calculation parameters for soil stress beneath the coastal dike included the dynamic force of waves $R_m$ of 2.07 ton, eccentricity $e$ of -0.37 m $<$ 2.08 m ($B_d/6$). Then, calculation of static force due to waves were presented as total moments of dike vertical load $MV$ of 438.12 (tm), total moments of wave horizontal load $MH$ of 17.95 (tm), and total vertical load $V$ of 63.42 (ton).

The factor of safety calculation results ($F_s$) are found less than $F_s$ of 2.0 or no safe for internal friction $\varphi_s$ of 10° and 15°, and more than 2.0 for for internal friction $\varphi_s$ of 20°. Therefore, this calculation results of $F_s$ for the internal friction $\varphi_s$ of 20° is compared by FEM-2D as explained below.

The steps for FEM calculation are as follows:
- Carry out soil and dike modeling,
- Input parameter of the material model of soil and dike,
- Prepare fixed soil ground,
- Generate mesh for ground and dike,
- Set up boundary conditions of the construction,
- Calculate initial pore pressure of the soil,
- Set up calculation of elasto-plastic with stage construction ($t = 0$ day),
- Run application program, and
- Check the calculation results of soil stress and displacement.

The calculation results of soil the stresses beneath the dike using an empirical equation and FEM-2D are listed in Table 4.

| Soil stress beneath the dike | Calculation result (t/m$^2$) | Allowable bearing capacity, $q_{bs}$ (t/m$^2$) | Remark |
|-----------------------------|------------------------------|-----------------------------------------------|--------|
| Maximum stress, $q_{max}$   | 5.97                         | $\sigma_s = 4.57$                            | Safe   |
| Minimum stress, $q_{min}$   | 4.17                         |                                               |        |

Table 4 shows that calculation result of soil stress beneath the dike with FEM-2D is found fitted to the empirical calculation method in equations of 5 and 6. Moreover, the allowable bearing capacity of soil foundation is obtained more than maximum stress ($q_{max}$) of 5.97 t/m$^2$. Those input soil and dike parameters above that applied in the empirical and Finite Element Methods are reasonable to use in the simulation.

5. Conclusions
The research summarized the following:
- The safety factors ($F_s$) of soil the bearing capacity is predicted for internal friction $\varphi_s$ of 20°.
- Calculation results for soil stress beneath the dike with the empirical method are fitted to FEM-2D by using the Mohr-Coulomb model with drained type material
- Calculation result for vertical displacement is evaluated at 12.5 cm, and
- Soil parameters are reasonable to use in simulations.
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