Study Internal Stability of Masonry Construction for the Fort Oranje Ternate

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Abstract. Based on information board data, the Fort Oranje Ternate founded in the year 1607. It was 412 years old, where Fort Oranje constructed by masonry with main materials of the coral river and coast marine with lime mortar. However, Fort Oranje at the south side was collapsed on August 24th, 2017. This research is to study the collapsing problem of the fort construction, authors were investigated in field and found a collapse area about 24 meters in length, and 5.7 meters in height. In visualization views show that fort construction failure due to internal stability indication. Therefore, to measure the physical and chemical parameters of Fort Oranje construction for calculation, authors are taken some mortar samples in the field, and bring it into laboratories. In which, mortar samples have to observe the quality by using a compression machine in Structure and material laboratory, chemical contents analyzed in the Chemical laboratory. Finally, the results of the compressive test machine for lime mortar are found on average about $\sigma'_c$ of 1.2 MPa and it is less than 19.9 MPa for normally mortar material with cement. Geometrical fort existing consisted of width at top $b_1$ of 0.70 m, width at bottom $b_2$ of 1.20 m, the total weight of masonry $W$ of 108.3 kN. Then, soil fill parameters such as bulk density $\gamma$ of 17.2 ~ 19.2 kN/m$^3$, internal friction $\phi_i$ of 16.5$^\circ$, cohesion $c \approx 0$, and height $h_{r}$ of 3.26 m. Finally, simulation results for height $h_k = 3.26 m \sim 3.9 m$ are obtained factor of safety for overturning $Fs_1 < 2.0$, Meanwhile, a factor of safety for sliding $Fs_2$ at the base are found $Fs_2$ of 1.43 ~ 1.53. Moreover, Chemical content analyzed by XRF test method for the lime mortar sample is obtained by dominating Calcium Oxide (CaO) of 78.81%.

Keywords: Collapsing problem, Masonry construction, Lime mortar, Fort Oranje.

1. Introduction

Fort Oranje founded 1607, it is located in Ternate City, North Maluku Province. Based on investigation and information in the field, there are several activities around the foundation such as cutting soil for drainage construction. On the other hand, the fort construction was 412 years old as shown in Figure 1. Figure 1(a) shows the fort construction indicates cracks at the floor before collapsing. It may be triggered by water intrusion from the floor into the soil fill during heavy rain.
Figures 1(b) and (c) shows the front views of the collapse area about 24 meters in length and 5.7 meters in height in the south area on August 24th, 2017. There are many activities of heavy equipment for constructing drainage project at the outside of the foundation.

Figure 1(d) shows detailed views of river stone and coral of marine stone with lime mortar for masonry constructing the fort. Several mortar materials for sampling are collected, and bring it into Laboratory Structure and material and laboratory of Chemical analysis. In order to calculate parameters for soil fill pressure inside forts, its soil fill material sampled and bring it into the Soil Mechanics laboratory.

2. Fundamental theory

To calculate stability internal for fort construction such as a factor of safety for overturning $F_{s1}$ and sliding $F_{s2}$. The cross-section of the fort collapse area measured the dimension of construction in the field. It is shown in Figure 2.
where, $P_a$ is an active force due to soil fill inside fort construction.

**Figure 2.** Detailed views of the fort construction for internal stability analysis

Figure 2 shows the idealization of the analysis model to provide a calculation of internal stability such as a factor of safety for overturning and sliding. The internal stability for Fort Oranje construction analyzed by following analysis of the gravity retaining wall [1, 2].

Kustiyah and Suyuti reported the results of uses of ash Vulcano of Gamalama mountain as material for stabilization of soil fill [3].

### 2.1 Factor of safety for overturning

The internal stability analysis of the fort construction for a factor of safety of overturning $Fs1$ can be written as [1]

$$Fs_1 = \frac{W \times b_v/2}{K_a \gamma_s h_k} + 1 > 2.0 \tag{1}$$

where $W$ is the weight of construction (kN), $b_v$ is the average of width at top and bottom (m), $P_a$ is the active force of the soil fill (kN), $\varphi_a$ is the angle friction of the active force ($^\circ$).

The active of soil pressure due to soil fill inside fort construction $P_a$ is calculated [2].

$$P_a = \frac{1}{2} K_a \gamma_s h_k$$

$$K_a = \tan^2 \left( 45^\circ - \frac{\varphi_s}{2} \right) \tag{2a}$$

where $K_a$ is the coefficient of active pressure at static condition, $\gamma_s$ is the unit weight of soil (kN/m$^3$), $h_k$ is the actual height of construction of segment-I (m), $\varphi_s$ is the internal friction of soil ($^\circ$).

### 2.2 Factor of safety for sliding

The internal stability analysis of the fort construction for a factor of safety of sliding $Fs2$ can be calculated by [1, 2]

$$Fs_2 = \frac{F_r}{F_d} > 1.5 \tag{3}$$

In which, the resistance force of the fort construction $F_r$ is predicted by

$$F_r = \sigma \tan \mu + b_r c_d \tag{4}$$

where $\sigma$ is the total pressure at the base of the collapsed segment (kPa), $\tan \mu$ is the coefficient of friction between coral stone and base of segment-II, $c_d$ is the adhesion factor of masonry.

The driving force due to soil fill inside of the fort construction $F_d$ is calculated by

$$F_d = P_a \cos \varphi_a \tag{5}$$
where $P_a$ is the active force of soil pressure due to soil fill (kN), $\phi_a$ is the angle friction of the active force ($^\circ$). The detailed parameters for analyses are shown in Figure 4.

3. The methodology of the study

3.1 Parameters for calculation

In the simulation of calculation of the internal stability, there are several parameters of fort construction, soil fill, and lime mortar at the collapsed area. The priority studied to focus on how to calculate the internal stability for overturning and sliding without quake.

![Sample model for compressing and extracting tests](image)

Figure 3. Sample model for compressing and extracting tests

3.2 Mathematical analysis for calculation

Therefore, authors have to survey dimensions of fort construction for calculations, which are provided by three points, $q_0$ is the surcharge pressure due to the floor of the fort as shown in Figure 4.

![Schematics of detail parameters used in analysis for calculation](image)

Figure 4. Schematics of detail parameters used in analysis for calculation
Here, horizontal force concerned at point-A with height \( h/3 \) from the base soil fill such as \( R;R_v \) and \( R_h \) are the resultant of horizontal force with angle \( \phi \), the vertical force and the horizontal force, respectively.

### 3.3 Simulation of factor of safety

To prepare proposal using empirical equations for calculating internal stability of the fort construction, the calculation steps are explained.

1) Soil investigation

Soil properties are investigated by conducting soil fill samples in the Soil Mechanics laboratory. It is tested to determine the unit weight, direct shear, and Atterberg limit tests. So, the soil fill parameters can be found such as cohesion \( c \) (kPa), internal friction \( \phi^o \), and unit weight of soil (kN/m\(^3\)).

### 4. Results and discussions

To identify the physical parameters of the fort construction, some lime mortar samples were conducted to observe mechanical forces in the laboratory (See Figure 3a). Here, those model samples are made dimensions of 5 cm \( \times \) 5 cm \( \times \)5 cm. The results of the compressive force are listed in Table 1.

**Table 1. Parameters of lime mortar sample test results**

| Sample | Lime mortar | Compressive force \( P \) (kN) |
|--------|--------------|---------------------------------|
|        | Weight (gram) | Unit weight (g/cm\(^3\)) | |
| 1      | 155          | 1.24                           | 1.0    |
| 2      | 175          | 1.40                           | 3.0    |
| 3      | 190          | 1.52                           | 6.0    |
| 4      | 165          | 1.32                           | 4.0    |
| 5      | 170          | 1.36                           | 1.1    |

Therefore, those compressive forces are calculated to identify compression strength \( \sigma_t \), as results are listed in Table 2.

**Table 2. Comparison of compression strength test results**

| Mortar material type           | Compression strength \( \sigma_t \) (MPa) | Remark            |
|-------------------------------|-------------------------------------------|-------------------|
| Lime mortar, Fort Oranje      | 0.4 (sample 1)                            | Laboratory test   |
|                               |                                           | 1.2 (2)           |
|                               |                                           | 2.2 (3)           |
|                               |                                           | 1.6 (4)           |
|                               |                                           | 0.4 (5)           |
|                               | Average \( \sigma_t = 1.2 \)             |                   |
| Ash mortar, Mt. Gamalama      | 0.8                                        | Laboratory test   |
| Cement mortar                 | 19.9                                       | Laboratory test   |

By using empirical equations for calculation, soil fill parameters are taken into calculation such as internal friction \( \phi \) of 26.5°, unit weight \( \gamma \) of 17.2 kN/m\(^3\) \( \sim \) 19.2 kN/m\(^3\), and coefficient of active pressure at static condition \( K_a \) of 0.382.

The actual height of soil fill \( h_k \) of 3.9 m, an average height \( h_r \) of 3.26 m. Therefore, the horizontal active force of soil fill \( P_a \) of 116 kN \( \sim \) 128.7 kN for height \( h_r \) of 3.26 m, while \( P_a \) of 138.6 kN \( \sim \) 153.8 kN for height \( h_k \) of 3.9 m (where surcharge load of the floor \( q_0 \) = 4 kN/m\(^2\)). The results of simulations are shown in Figure 5.
Figure 5. Results of factor of safety Fs for collapsing area of the fort construction

Figure 5. shows factor of safety for overturning $F_s1$ calculated by using parameters such as weight $W$ of 108.3 kN (where $b/2 = 0.475$ m), the angle friction for lateral force $P_a$ assumed $\phi$ of 31.3° for a height $h/3b$ of 1.5 m. The dimensions of construction are height $h_b$ of 3.26 m, vertical force $P_v$ of 60.25 ~ 66.85 kN. Meanwhile for height $h_k$ of 3.9 m, defined $W_xb/2 = 51.44$ kN, vertical force $P_v$ of 72.01 ~ 79.91 kN for both per 1 meter in length.

The chemical content dominated Calcium Oxide (CaO) and Silica about 5.35%. The completion results of XRF tests for lime mortar sample are shown in Figure 6.

Figure 6. Sample test results using ERF test for lime mortar sample

5. Conclusions

The calculation of the simulation results of this research can be concluded as below:

a) The compression strength of lime mortar by machine tests resulted $\sigma_t'$ of 1.2 MPa, and it is less than ten times by compression strength of the cement mortar $\sigma_t'$ of 19.9 MPa.

b) The results of simulation calculation of the factor of safety for overturning $F_s1$ is not safe for internal stability ($F_s1 < 2.0$).

c) The results of simulation calculation of the factor of safety for sliding $F_s2$ is not safe for internal stability ($F_s2 < 1.5$).

d) The result of ERF tests of lime mortar for chemical content is dominated by Calcium Oxide (CaO) of 78.81%. It is strongly evidenced that the material of mortar made by lime of coral of marine stone.
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