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Original Article

Stability Analysis of Gravity Retaining Wall by DEM Simulation

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Abstract: *For the conventional retaining wall in a kind of gravity wall, the weight of the structure influences the stability of the retaining wall. Moreover, the weight of the retaining wall is determined by its dimension. The assumptions of retaining wall dimension are determined by trial and error. If the retaining wall is not enough to bear the load, the dimension of the retaining wall must be changed. In this study, we analyze a gravity retaining wall according to Rankine's theory. The active earth pressure and passive earth pressure have been calculated using Rankine's theory and the stability of the retaining wall against sliding, overturning, and bearing capacity is also calculated. Finally, the stability is compared through discrete element modeling simulation. As a limitation of this study, there is only one layer of backfill material considered due to simplicity. Given the hypothetical computation and DEM simulation results, the gravity retaining wall shows slight sliding and overturning failure. There is no bearing capacity failure for this structure. As there are no micro-cracks found in the simulation, it justified the theoretical calculations.*

Keywords: *Gravity Retaining Wall, Rankine's Theory, DEM.*

I. INTRODUCTION

Conventional retaining walls can be divided into four types: gravity, semi-gravity, cantilever, and counterfort retaining walls. The gravity retaining wall type is formed by concrete, stone, or a combination of both. Moreover, a semi-gravity wall is constructed by modifying gravity walls. The semi-gravity walls use steel that can minimize the size of wall sections. On the other hand, a cantilever retaining wall is formed of reinforced concrete that consists of a thin stem and a base slab. Moreover, the type of counterfort retaining wall has a similar shape to a cantilever but at some intervals, they have counterforts that tie the wall and the base slab together. The counterforts mean thin vertical concrete slabs. Each type of retaining wall can be seen in Fig 1

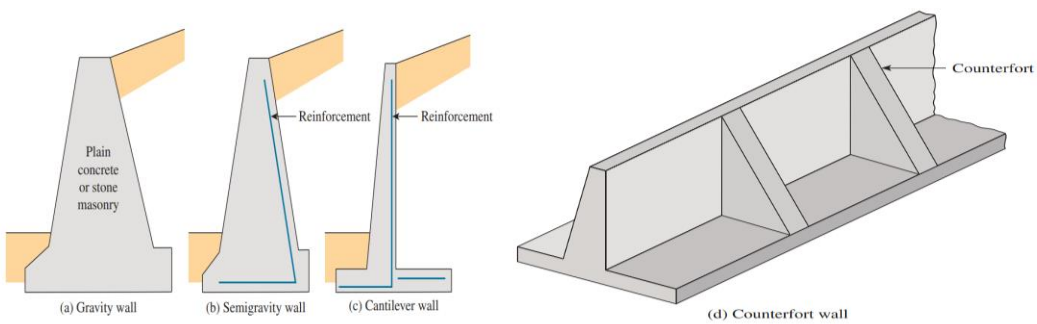

Figure 1: Types of retaining wall

II. DESIGN OF GRAVITY WALL

The failure surface of the retaining wall can be reviewed with its safety factor. Calculating the safety factor can be done using empirical equations or modeling simulation. Figure 2 show that there is only one backfill material, with a unit weight of 26.7 kN/m3 and a friction angle of 35.5.

Table 1: Material properties of soil and retaining wall

MATERIAL PARAMETER	DESIGN VALUES
BACKFILL MATERIAL	soil
UNIT WEIGHT OF BACKFILL MATERIAL	26.7
COHESION	58.36
FRICTION ANGLE	35.5
UNIT WEIGHT OF CONCRETE	24

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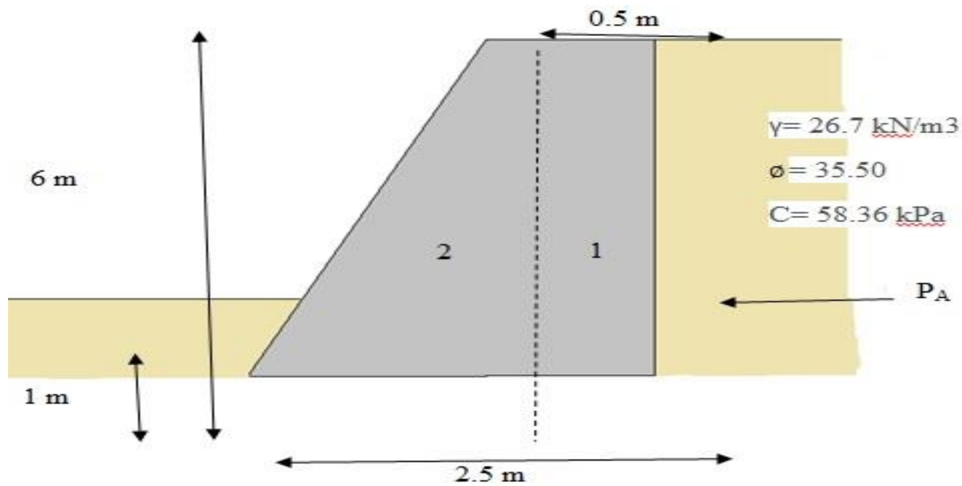

Figure 2: Gravity retaining wall as a case study

III. THEORETICAL ANALYSIS OF RETAINING GRAVITY WALL:

Using Rankine's theory

A. The factor of safety against overturning

Active earth pressure coefficient:

Angle of friction(∅)=35.5

$$Ka = (1-\sin\emptyset)/(1+\sin\emptyset) = (1-\sin(35.5))/(1+\sin(35.5)) = 0.266$$

$$Pa = ½*Ka*\gamma*(h)^2$$

Where ka is Rankine's active earth pressure coefficient; γ is the unit weight of soil and h is the height of the retaining wall.

$Pa=1/2*0.266*26.7*(6)^2$

Pa =127.84KN/m

Weight	Magnitude	Moment Arm	Moment About C
W1=0.5*6*24	72	2.5+0.5/2=2.75	198
W2=1/2*2.5*6*24	180	2/3*2.5=1.66	300.6
Pa*h/3=127.84*6/3	-	-	-255.68
	∑v=252KN		∑M=242.92KN.m/m

The factor of safety against overturning:

$$FSo=\frac{\sum MR}{\sum M0}$$

Where,

∑MR=sum of the moments of forces tending to resist overturning about point c

∑Mo=sum of the moments of forces tending to overturn about point c

$$Fso=\sum\frac{198+300.6}{255.68}$$

FSo=1.95

The factor of safety against Overturning=1.95

B. The factor of safety against sliding:

$\delta=2/3\ \emptyset'=2/3*35.5=23.67$

$\mu=\tan(23.67)=0.44$

The factor of safety against sliding:

$$FS(sliding)=\frac{\sum FR\prime}{\sum Fd}$$

Where,

∑FR'=sum of the horizontal resisting forces

∑Fd=sum of the horizontal driving forces

$$\sum FR' = (\mu \sum v) , \sum Fd = Pa$$
$$FS(\text{ sliding}) = (\mu \sum v)/Pa$$

FS sliding =(0.44*252)/127.84
FS sliding =0.87
The factor of safety against Sliding=0.87 <1.5 so (not ok)

IV. FACTOR OF SAFETY AGAINST BEARING CAPACITY FAILURE

The base of the retaining wall can be treated as a strip foundation that is subjected to a line load, which can act eccentrically and with some inclination to the vertical.
The eccentricity of the resultant force is given by,
$e=\frac{B}{2}-x$

$$x=\frac{\sum MR-M0}{\sum V}=\frac{498.6}{252}=1.98$$

e=1.5-1.98
e=0.48
$\frac{B}{6}=\frac{3}{6}=0.5$
$e<\frac{B}{6}$

The maximum and minimum pressure occur at $y=\frac{B}{2}$ and $-\frac{B}{2}$Respectively.

$$q_{max}=\frac{\sum v}{B}(1+\frac{6e}{b})$$

$q_{max} =\frac{252}{6}(1+\frac{6*0.48}{3})$
q_{max} =164.64 KN/m^2
$q_{min}=\frac{\sum v}{B}(1-\frac{6e}{b})$
$q_{min} =\frac{252}{6}(1-\frac{6*0.48}{3})$
q_{min} =3.36KN/m^2

Treating the base of the retaining wall as a continuous foundation(with shape factors Fcs, Fqs, and Fγs being unity), qu can be written as

$$qu = cNcFcdFci+qNqFqdFqi+\frac{1}{2}\gamma B'N\gamma F\gamma dF\gamma i$$

where,

$$q=\gamma D$$
$$B'=B-2e$$
$$Fqd=1+2\tan\phi(1-sin\phi)^2(\frac{D}{B'})$$

Fqd =1+2tan(35.5)((1-sin35.5)^2)($\frac{1}{2.04}$)
Fqd=1.13

$$Fcd=Fqd-\frac{1-Fqd}{NC(tan\phi\ \ )^2}=1.29-\frac{1-1.29}{48.35*tan(35.5)^2}=1.30$$

B'=B-2e=3-2(0.48)=2.04m
$F\gamma d = 1$
Fci=1
Fγi=1
Fqi=1
qu = (58.3*48.35*1.30*1) + (26.7*1)*(1.13)*(1) +0.5*(26.7*2.04*52.17*1*1)
qu =5115.42 KN/m^2
Fs (bearing capacity) = $\frac{qu}{qmax}=\frac{5115.42}{164.64}=31.07$
The factor of safety against bearing capacity failure=31.07 >6 so (ok) But it is not economical.

V. DEM SIMULATION

PFC2D (Particle Flow Code in two dimensions), a software based on the principle of the discrete element method (DEM), was used to analyze the stability of the retaining wall. Compared with the continuum approach such as finite element analysis, DEM does not need the definition of macroscopic constitutive models. The micro parameters need to be ascertained by trial-and-error method to match the macroscopic properties of specimens.

In DEM simulation, all materials are treated as aggregates of disks in 2D with different contact models. As shown in Figure 3, there are a total of 15,611 particles in this model with a radius from 0.04 m to 0.0664 m.

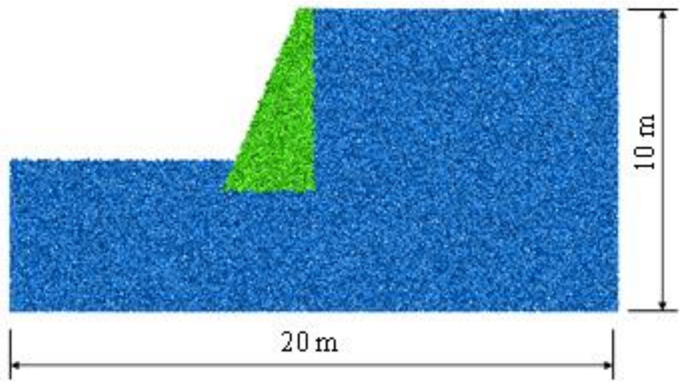

Figure 3: Schematic Diagram of DEM Model

In this study, the linear parallel bond contact model was used to build the gravity wall, and the linear contact bond model was used to build soil. As shown in Figure 4, when the gap between two particles is less than the limit values, the contact model will contact these two particles, and when the stress of contact exceeds the specified shear or tensile strength, the contact will break. The key to DEM simulation is the calibration of micro parameters. Typically, calibration is performed through matching simulation results and test data. In this study, we referred to the values of micro parameters in previous papers. The micro parameters used in this study are shown in Table 2.

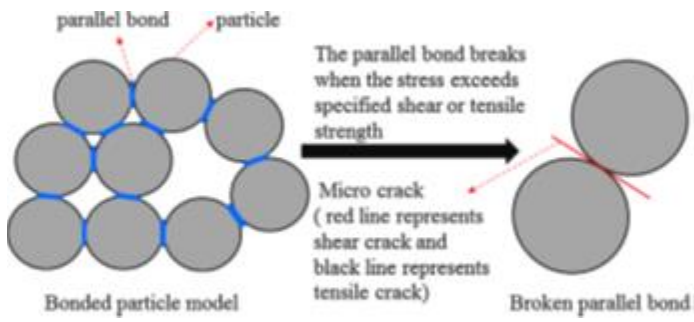

Figure 4: Schematic Diagram of the Bonded Particle Model and the Broken Parallel

Table 2: Micro-parameters for DEM simulation

	Micro Parameter	Value	Micro Parameter	Value
Prallel Bond Model	**Density(kg/m3)**	**2400**	**Friction coefficient**	**1.2**
	Modulus(GPa)	**1**	**Stiffness Ratio**	**1**
	Normal Strength(MPa)	**10**	**Shear Strength(Mpa)**	**50**
Linear Contact Model	**Density(kg/m3)**	**2670**	**Friction Coefficient**	**1.2**
	Modulus (MPa)	**25.3**	**Stiffness Ratio**	**1**
	Normal strength(kPa)	**8**	**Shear Strength (kPa)**	**8**

All particles were assigned a gravity of 9.81 N/kg. When the displacements of particles have no significant change, the model is considered to be in equilibrium. The stability of the gravity wall against overturning, sliding, and bearing capacity failure was analyzed through the displacement and contact force figures.

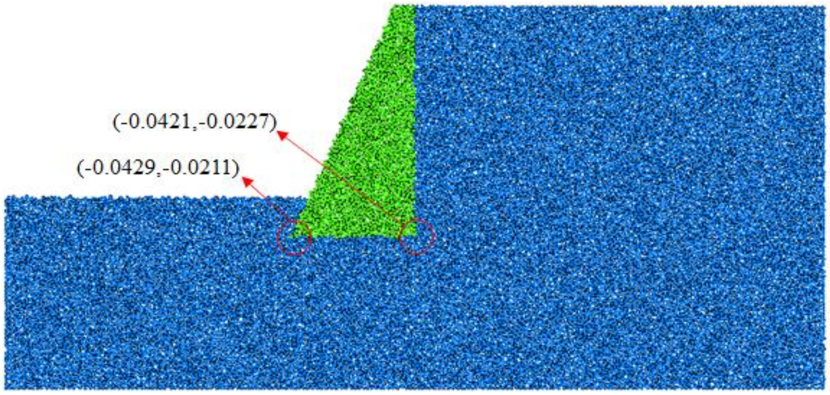

Figure 5: Schematic Diagram of Displacement

Figure 5 shows the displacement of the model when it reached the equilibrium. The displacements at the toes of the gravity wall are (-0.429,0.0211) and (0.0421,-0.0227), which shows that the retaining gravity wall has slight sliding and overturning. There are shear forces around the gravity retaining wall as shown in figure 6, which proves the settlement and sliding of the gravity retaining wall. There is no bearing capacity failure because no micro-cracks appear in the gravity retaining wall.

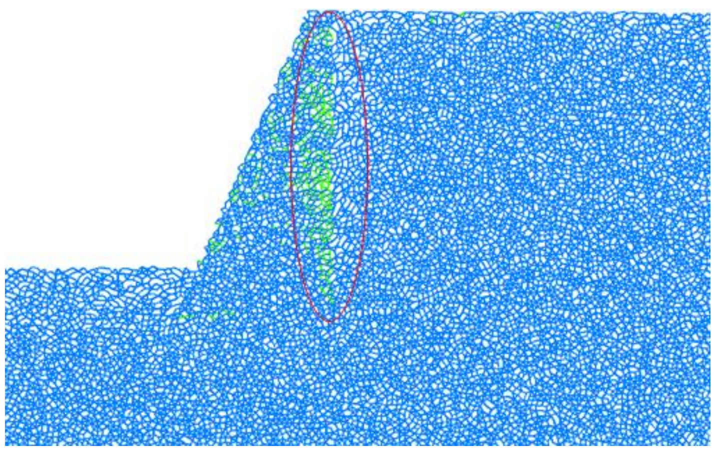

Figure 6: The Contact Force of the Numerical Model (Blue Lines Mean Compressive Force and Green Lines Mean Shear Force)

VI. CONCLUSION

Based on the theoretical calculation and DEM simulation results, the gravity retaining wall designed in this study has slight sliding and overturning. There is no bearing capacity failure because no micro-cracks appear in the gravity retaining wall, which is consistent with the theoretical calculations.

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