Effect of cemented layer formation on liquefaction potential of coal ash pond

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ABSTRACT

In this study, the liquefaction potential of Taichung coal ash pond under the effect of cemented layer formation is assessed. A 3D finite element framework for earthquake engineering simulation (OpenSeesPL) was adopted to analyze the pore pressure change and horizontal ground displacement of coal ash pond during earthquake. The coal ash pond had a very weak layer below GL -7.0 m, which was hydraulically filled below the mean sea level. This layer is very likely to liquefy under strong earthquake excitation such as Chi-Chi earthquake. If cement is added during the hydraulic filling process, an interlayered cemented-uncemented layer formation can be formed due to particles segregation during settling process. The cemented coal ash layer (the upper layer) will not liquefy, but the uncemented layer (the lower layer with larger particles size) will liquefy under strong earthquake. So the relative thickness of cement and uncemented (untreated) coal ash layer is a crucial factor to assess the liquefaction potential and the maximum horizontal displacement of the coal ash pond. The influence of the relative thickness on liquefaction will be evaluated by initial liquefaction time, total liquefaction time and maximum ground displacement. In general, the initial liquefaction time is not affected by the thickness of cemented layer; the time to reach total liquefaction depends on its location or the thickness of the cemented layer. The maximum horizontal ground displacement is directly proportional to the thickness of liquefiable coal ash layer. In fact, it can be said that forming a cemented layer formation in the coal ash pond is an effective way to restrain the horizontal ground displacement of coal ash pond during liquefaction.

Keywords: coal ash pond; liquefaction; cemented coal ash; OpenSeesPL; excess pore pressure

1 INTRODUCTION

The coal ash generated from the coal burning power plants in Taiwan was mostly dumped to the nearby coal ash ponds located along the coastline by hydraulic filling method. The hydraulically deposited coal ash is often loose and prone to liquefaction during earthquake, especially when it was dumped underwater. Recently, coal ash ponds have been considered to be the site for future expansion of the power plants. Therefore, how to avoid liquefaction of coal ash pond was studied by the power companies. Among the possible methods, adding cement in the discharge pipeline during hydraulic filling process is studied here. This method allows the construction be started as soon as the hydraulic filling process is completed. Such a cement addition method will form a layered coal ash formation inside the coal ash pond. The cement-coal ash formation above the sea level has good density. However, due to segregation problem of cement and coal ash particles during underwater filling, a layered structure with cement and fine particles of coal ash settle on top of the layer consisting of large size coal ash particles with trace of cement. Previously, Mohanty & Patra (2016), and Vijayasri et al. (2016) used the open system for earthquake engineering simulation (OpenSees) to obtain the liquefaction response for coal ash pond in India. In comparison, this research used a 3D finite element (OpenSeesPL, modified from OpenSees) to simulate the liquefaction response of coal ash pond with and without soil improvement under earthquake excitation.

2 TEST SITE DESCRIPTION

The site investigation data shown that the Taichung coal ash pond can be classified as silt to silty sands (ML-SM) by the AASHTO soil classification method. As shown in Fig. 1, the soil profile of a depth up to 16.0 m can be divided into four layers, the top two coal ash layers were above the mean sea level; a lower coal ash and seabed layer were below the mean sea level. The ground water level is at GL -2.5 m. Of the three coal ash layers, the unit weight = 12 to 16 kN/m^3; specific gravity = 2.25 to 2.38; and void ratio > 1.2; fines content up to 85%. But the top two coal ash layers had higher strength (SPT-N = 2~16) than the lower one (SPT-N < 2). In the contrast, the seabed layer consists of alluvial sand with SPT-N value up to 15, fines content around 15%, and a unit weight of 19.5 kN/m^3.

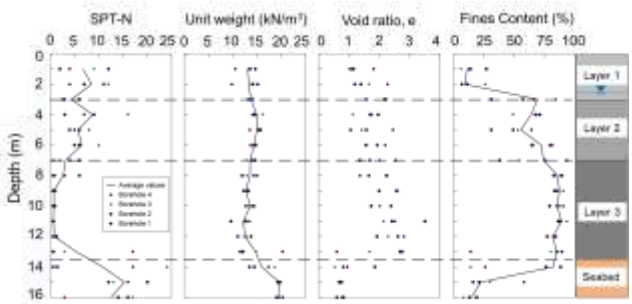

Fig. 1. Physical properties of coal ash pond in Taichung, Taiwan

3 NUMERICAL SIMULATION

3.1 Simulation platform

Because of two reasons, the OpenSeesPL was used as a functional tool in this analysis. Firstly, it can capture the large displacement compared to other finite elements. Secondly, it can determine the liquefaction parameters relatively easier in the OpenSeesPL. OpenSeesPL program - a graphical user interface for researching 3D seismic (earthquake) analyses (Lu, Elgamal, & Yang, 2011) had been used as the computational platform to assess the liquefaction potential based on the maximum displacement at ground surface and excess pore water pressure response in the coal ash layers.

3.2 Finite element model

In view of symmetry, a half-mesh configuration of 4080 elements (8-node brick elements) is adopted here (Fig. 2). The dimensions of the model are 20 m: 10 m: 20 m (longitudinal: transverse: vertical). The periodic boundary is applied to reproduce a 1D-shear wave propagation mechanism effect. A damping ratio of 2% is selected for the site response analysis at frequencies of 2 and 5 Hz to avoid numerical instability. In the numerical simulation, a shaking load was assigned at the base of the model (GL -20 m); therefore, the recorded motion of Chi-Chi earthquake at the seismology station TCU070 at ground surface was used to deconvolution the acceleration signal at the depth of 20.0 m as shown in Fig. 3.

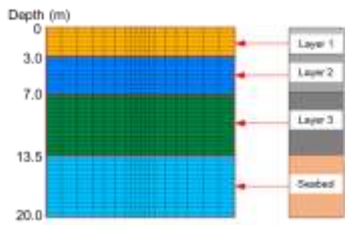

Fig. 2. Finite element mesh

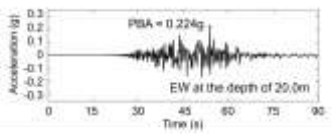

Fig. 3. Base input motion to OpenSeesPL

3.3 Soil constitutive model

In OpenSeesPL, a constitutive model (Pressure Depend Multi Yield - PDMY) is available to conduct the liquefaction analysis for cohesiveless soils under seismic excitation (Yang et al.2003). The PDMY model is derived from the original framework of multi-yield plasticity for cohesiveless soils with an additional new flow function. As for the input parameters for PDMY model, a set of data including soil nonlinear, fluid and liquefaction properties is assigned based on values suggested in the manual. Among them, only the soil elastic properties (G_{max}, B_{max}) need to be calibrated using Eq. (1).

$$G_{max} = \rho V_s^2;\ B_{max} = G_{max} \times \frac{2(1+\nu)}{3(1-2\nu)} \qquad (1)$$

Where V_s is shear wave velocity and ν is Poisson's ratio.

4 MATERIAL PROPERTIES FOR ANALYSIS

Since no theory or empirical equations in evaluating the liquefaction potential of coal ash in pond has been proposed yet. Therefore, the coal ash pond is assumed to be similar to sandy soils here and used the parameters provided in OpenSeesPL. In this section, field test results of the coal ash pond are used to estimate the corresponding relative density of clean sands in order to choose the adequate liquefaction parameters from OpenSeesPL.

4.1 Material properties of untreated coal ash

The relative density and soil elastic properties of untreated coal ash pond are depicted in Table 1.

Table 1. Input parameters for coal ash pond in OpenSeesPL

No. Layers	Depth (m)	ρ (t/m^3)	D_r (%)	G_{max} (kPa)	B_{max} (kPa)	LQ parameters*
1	1	1.30	53.0	49885	130092	**Medium Sand**
	2	1.32	49.4	50463	131600	
	3	1.37	46.4	57998	151249	
2	4	1.49	62.1	82281	214577	**Medium Sand**
	5	1.5	50.1	82696	215659	
	6	1.43	56.0	79101	206282	
	7	1.36	40.9	75090	195824	
3	8	1.35	38.6	24697	64405	**Loose Sand**
	9	1.27	20.3	23187	60469	
	10	1.36	19.8	24834	64763	
	11	1.22	19.2	22227	57964	
	12	1.25	20.8	22822	59515	
	13.5	1.46	52.5	26755	69772	
4	13.5~20	2.00	-	2.40000	520000	**Dense Sand**

(*) Input LQ parameters are shown in OpenSeesPL User manual.

4.2 Material properties of cemented coal ash layer

From the field test results, it had been found that the cemented coal ash layer had the SPT-N value was around 42 and with little or no fines content. It is assigned as clean sand at dense state ($D_r > 85\%$) here. The input parameters are presented in Table 2.

Table 2. Input parameters of cemented coal ash in OpenSeesPL

Parameters	Cemented Coal Ash
Wet unit weight, ρ (t/ m^3)	1.65
Shear modulus, G (kPa)	1.93E05
Bulk modulus, B (kPa)	3.2E05
Permeability, k (m/s)	2.5E-08

5 SIMULATION RESULTS AND DISCUSSIONS

Since the pore pressure response changes very rapidly with time during earthquake, it is hard to exactly pin point the moment when the excess pore pressure ratio, EPPR (r_u) value is equal to 1.0. So the occurrence of liquefaction is defined when r_u values of the soil increase to 0.95~1.0 in this research. The liquefaction defined here can be further divided into initial liquefaction (initial LQ) and total liquefaction (total LQ). The former is the moment when the maximum excess pore pressure at any place in the liquefiable layer firstly reaches the initial effective overburden pressure ($r_u = 1$); the latter is the moment when the excess pore pressure of large portion of the liquefiable layer reaches the initial effective overburden pressure and its r_u remains a constant value of about 1.0.

5.1 Liquefaction analysis for untreated coal ash pond

Fig. 4 shows that the first layer (GL 0 to -3.0 m) is not liquefied because the ground water level is low at GL -2.50 m. Similarly, the second layer (GL -3.0 to -7.0 m) and seabed layer (below GL -13.5 m) do not liquefy because their r_u values do not reach 0.95. By contrast, liquefaction occurs at the coal ash layer below the mean sea level (i.e., the third layer at GL -7.0 to -13.5 m) when its r_u value reaches about 1.0. Apart from the coal ash at shallow depth, the initial liquefaction and total liquefaction of the liquefiable layer (the third layer) occurred after the Chi-Chi EQ shaking for 31.08 and 51.31 seconds respectively (Figure 5). However, liquefaction does not occur throughout the entire liquefiable layer (third layer). A thin upper part (GL -7.0 to -8.0 m) of the liquefiable layer does not liquefy, while the rest of the layer liquefies. To figure out this phenomenon, a sample layer which has the same thickness and soil properties as the third layer has been conducted in the simulation. But it is placed on the ground surface rather than 7 m below ground surface and the groundwater level is set at the ground surface.

Excess pore pressure response throughout the liquefiable layer (the third layer) at different depths is displayed in Figure 5. It indicates that when the liquefiable layer is right at the ground surface, the entire sample layer is liquefied. The initial liquefaction occurs at GL -0.5 m (29.30 seconds after the shaking started) and propagates downward. After shaking for about 38.90 seconds, the entire layer liquefies (total LQ). The pore pressure behavior of the example layer generated from the OpenSeesPL framework and its constitutive material model is reasonable and as expected.

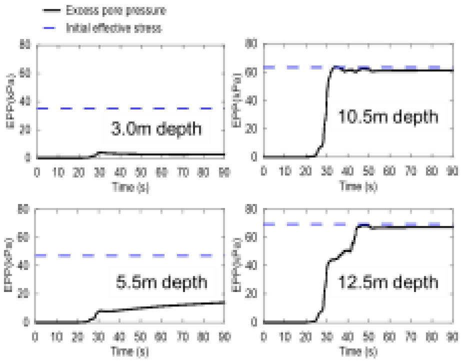

Fig. 4. Variations in excess pore pressure with time at different depths (4080-element mesh)

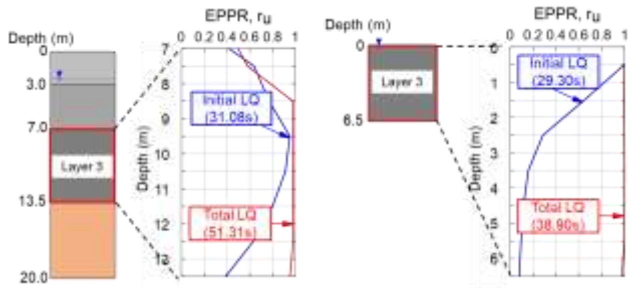

Fig. 5. Variation of excess pore pressure ratio in the liquefiable layer at initial and total liquefaction moments

5.2 Liquefaction analysis for cement-coal ash formation

The coal ash deposited below seawater is liquefied without any soil improvement. Therefore, an attempt is made to assess the effect of location and relative thickness of the cemented coal ash layer on liquefaction resistance in this section.

a. Effect of cemented layer location in liquefiable layer

An overall comparison in the EPPR and maximum ground displacement in case of a 3.0 m cemented layer placed at the lower part (a) with that at the upper part (b) of the third layer is addressed. Fig. 6 shows that placing the cemented layer at the upper part of the liquefiable layer can decrease the maximum horizontal ground displacement more. The maximum ground displacement is reduced from 29.6 to 24.6 cm. These results may prove that using soil improvement for soil at shallower depths is more effective in restraining ground deformation.

b. Effect of cemented layer thickness in liquefiable layer

A simple simulation with a layer of cemented coal ash, t (m) overlain the untreated coal ash, s (m) is studies. Ranging from 1.0 to 6.0 m, a various thickness of cemented ash layer had been utilized to determine its influence on liquefaction potential of the coal ash pond. Table 3 and Fig. 7 present the computed results with various thickness of the cemented layer. It indicates that increasing thickness of cemented coal ash layer actually results in decreased maximum. For instance, a record of three-time smaller maximum displacement in case of 6.0 m of the cement-coal ash formation (11.71 cm) is observed than case of without soil improvement (36.1 cm). Furthermore, Table 3 implemented that the maximum displacement at the ground surface and the interface between cemented and not cemented coal ash layers are almost same. It means that the displacement is mainly resulted from the untreated coal ash pond.

In Fig. 7, the cemented coal ash layer in all conducted simulations are observed not to liquefy with smaller r_u values (0.2~0.6). Whereas, the untreated coal ash layers are highly liquefied. It is seen that the initial liquefaction time (during 29.92 seconds to 31.6 seconds after Chi-Chi earthquake shaking) is roughly same for these six simulations. On the other hand, the moment obtaining the total liquefaction gradually increases with thickness reduction of the cemented layer. In case of 6.0 m of cemented layer, the untreated coal ash (0.5 m) is liquefied only after 40 seconds of seismic excitation, while it takes 14.47 seconds longer to liquefy for 1.0 m of the cemented layer.

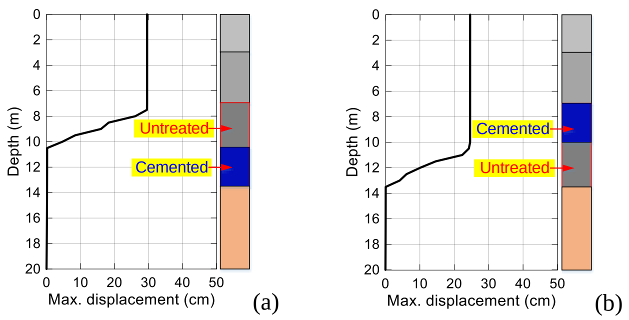

Fig. 6. Maximum displacements with depths in cases cemented layers at the lower part (a), upper part (b) of the third layer

Table 3. Computed results vs. various thickness of cemented layer

t (m)	s (m)	Time for initial LQ (s)	Time for total LQ (s)	Max. displacement (cm) At ground surface	At interface
6	0.5	30.94	40	11.71	11.70
5	1.5	29.92	42.35	22.79	22.79
4	2.5	30.25	46.79	24.50	24.49
3	3.5	30.28	51.77	24.61	24.61
2	4.5	30.51	53.88	29.63	29.62
1	5.5	31.6	54.47	31.4	31.39
0	6.5	31.08	51.31	36.1	36.05

6 CONCLUSIONS

Based on the numerical study using OpenSeesPL, the following conclusions can be drawn:

- After adding cement to the liquefiable coal ash layer, the cemented coal ash becomes non-liquefiable. With the cemented coal ash on the upper part of the liquefiable layer, it can reduce the maximum displacement by 5 cm at the ground surface compared to that of cemented coal ash layer is at the lower part of the liquefiable layer.
- By increasing the thickness of cemented coal ash layer at the upper part of the cemented-untreated coal ash formation, the maximum displacements at the ground surface can be proportionally reduced.
- The time to reach initial liquefaction of the untreated layer in the cement-coal ash formation is not much affected by changing the thickness of untreated coal ash layer (= ~30 seconds). If the horizontal displacement is the concern, the untreated coal ash is the main source to reduce the amount of displacement. So for the case studied here, the thickness of the untreated coal ash layer is kept below 3.5 m to make the horizontal displacement below 25 cm.

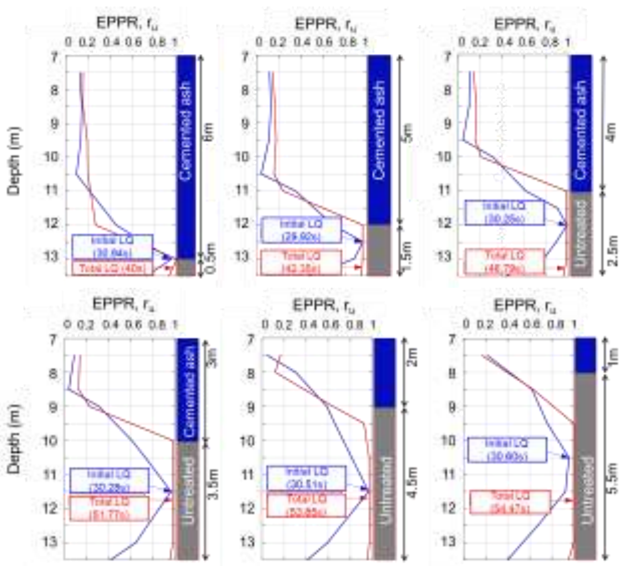

Fig. 7. Excess pore pressure response at specific times vs. various thickness of cemented ash layer

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