Lessons from the catastrophic landslide of construction waste dump occurred in Shenzhen of China on 20th December 2015

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ABSTRACT: On 20th December, 2015, a catastrophic landslide occurred in a waste dump located in Hongao Village, Shenzhen, China, which destroyed 33 buildings, killed 77 people and caused direct economic losses of 880 million yuan. In this study, the dump structure before sliding is reconstituted at first; the failure process and generation of excess pore water pressure are reproduced in a centrifuge test; the undrained shear strength of construction waste is tested by unconsolidated and undrained triaxial tests to clarify the failure mechanism; limit equilibrium analysis of stability, using undrained strength parameters, is made to compare the failure mode with undrained condition to the real mode in Shenzhen landslide; finally, lessons learned from this event are concluded, and corresponding measures are proposed with the purpose to prevent this kind of disaster from happening again.

1 INTRODUCTION

With the developing of urbanization in China, the exploitation of urban underground space has become an important way to ease the pressure on urban space, while the dramatic increase in construction waste leads to some new problems in recent years. According to rough statistics, the annual production of construction waste in China is about 3.5 billion tons, including about 1.5 billion tons of building waste and about 2 billion tons of construction waste (Dong et al. 2016). Taking Shenzhen as an example, the production of construction waste is about 36 million m^3 per year during 2013 to 2015 (Xu et al., 2016). The waste produced from the underground space excavation in the coastal areas of China is often characterized by high water content and low permeability, and it is difficult to be directly used. At present, the common disposal method is landfilling, and many cities have built or are building waste dump to help relieve the increasing pressure of construction waste disposal. In Shenzhen, more than 61% of the construction waste was transported to the 7 running waste dumps during 2013-2015; 45 dump sites are in planning and 2 existing landfills will be expanded. The capacity of a waste dump can up to 30 million m^3 and the filling height may be more than 100 meters.

During landfilling, unprofessional operations may lead to disaster since some waste dumps are located close to cities or residence area. On 20th December, 2015, a catastrophic landslide occurred in a 110-m-high waste dump located in Hongao Village, Shenzhen, China. The landslide involves 2.51×10^6 m^3 of construction waste and has a length of about 1100 m, which is the largest landfill slope failure in the world (Yin et al., 2016). The landslide destroyed 33 buildings and killed 77 people, causing direct economic losses of 880 million yuan (Zhan et al. 2018). To prevent similar disasters from happening again, it is indispensable to have detailed and comprehensive research on the failure mode and mechanism.

In the past two years, there were a lot of studies about this landslide, which focus mainly on numerical simulation and field investigation (Gao et al., 2017; Liang et al., 2017; Ouyang et al., 2017; Xu et al., 2017; Yin et al., 2016; Zhan et al., 2018).

In this study, the dump structure before sliding is reconstituted by geotechnical investigation; the failure process and generation of excess pore water pressure are reproduced in a centrifuge test; the undrained shear strength of construction waste is tested by unconsolidated and undrained triaxial tests; based on the relationship between shear strength and confining pressure (or degree of saturation). The failure mechanism is investigated by the limit equilibrium analysis of slope stability, using undrained strength parameters. The failure mode is obtained with undrained condition, which is then compared with the observed slope failure mode. Finally, lessons learnt from this event are summarised, and related future works are proposed with the purpose to prevent this kind of disaster from happening again.

2 RECONSTITUTION OF DUMP STRUCTURE

2.1 *Geotechnical profile of the waste dump*

Based on site investigation, *in-situ* tests, laboratory tests, multi-temporal remote sensing images and dump operation record, the pre-failure geotechnical profile of Shenzhen Hongao waste dump is rebuilt in Figure 1. Before dumping, the original field is an abandoned quarry with a layer of spoil waste above the granite bedrock. The dumping operation contains mainly two stages. During the first stage, from February to November 2014, the terraces T1-T4 were shaped with a fast filling rate of about 7 m/month and a maximum elevation of 115 m. The soil with low water content was filled in the front part at first to act as a dam when the construction waste with high water content and a volume of 1.24×10^6 m^3 was dumped into the rear area (see Figure 11(a) in Zhan et al., 2018). The second stage started from April 2015 after a mandatory closure due to the absence of environmental assessment. Till the beginning of December 2015, the height of the waste dump increased with a filling rate of 5 m/month to a maximum elevation of 160 m. Low-water-content construction waste was filled mainly above the high-water-content area in this stage. Hence, two units of different water content was formed during the filling process. The overall gradient of the slope from T1 to T9 is 4H/1V (14°), which is moderate. The total volume of the fill is 5.83×10^6 m^3, which is much greater than the designed capacity 4.0×10^6 m^3.

After the landslide, fourteen boreholes were drilled in the landslide area. The slip surface is determined to locate at a depth of 15-20 m below the surface after sliding, as indicated by the red line in Figure 1. It has a gentle inclination of about 6°.

The topography of the original site is bowl in shape with an impermeable bedrock. No effective interception trenches and drainage facilities were constructed to avoid water accumulation in the waste dump during the almost two years' filling. Based on water balance and seepage analysis, the total amount of water accumulated in the dump during the operational period is estimated to be 5.3×10^5 m^3, and the phreatic surface is determined as indicated by the blue line in Figure 1, with an elevation change from 118 m at the rear part to 85 m at the front part.

2.2 *Physical and mechanical properties of fill materials*

The main compositions of the construction waste in Shenzhen Hongao waste dump are 95% excavated soil and less than 5% brick, concrete and domestic garbage. The dominant component of the excavated soil is completely decomposed granite (CDG). 96 CDG samples were obtained from five boreholes in the landslide bed of the site. The particle size distribution tests show that the CDG was composed of 7%–24% gravel, 44%–72% sand, 12%–39% silt and 6%–10% clay. A typical CDG sample has the plastic limit of 20.5%, the liquid limit of 39.7% and the plastic index of 19. The CDG is classified as clayed sand (ASTM D2487, 2011). The average dry density for the 96 CDG samples is 1.44 g/cm^3, and the average water content is 24.6% (by mass). The specific gravity of CDG is 2.68, and so the average degree of saturation is 91.8%. Most of the borehole samples were saturated or nearly saturated which is consistent with the high groundwater level stated above.

The maximum and minimum dry density of the CDG were found to be 1.75 g/cm^3 and 1.20 g/cm^3 respectively. Hence, the average relative density of the 96 CDG samples are calculated. 14% of the samples were less than 0.33; 67% were between 0.33 and 0.67, and only 19% of them were greater than 0.67. It means that 81% of the CDG samples were in a loose or medium-dense state.

Thirty-one cut-ring samples were taken from the shallow layer of the residual waste dump around the source area for the measurements of dry density and water content. Four sand replacement tests were conducted to measure the in-situ dry density at the compacted terrace surface and the non-compacted sloping surface. Only three test points within a depth of 0.1 m below the terrace surface of T6 have a dry density close to or beyond 90% of the maximum dry density from compaction test. The dry density for the sloping surface measured by the sand replacement method was only 1.2 g/cm^3. The test points at the relatively dry front part have a water content range from 17% to 25%, corresponding to a degree of saturation between 49% and 80%. The measured water content of the wet rear part ranged from 31% to 33% and the degree of saturation varied from 81% to 94%. The low values of dry density indicate that the upper part fill of the waste dump was not well compacted. It is revealed in the investigation after the landslide that no timely and effective compaction

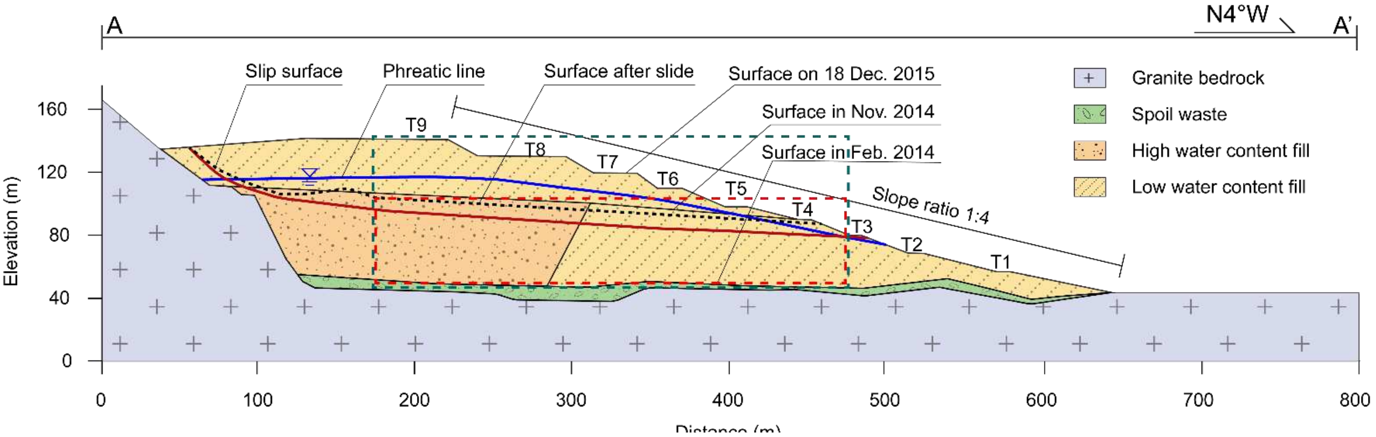


Figure 1. Typical geotechnical profile of the waste dump before failure (Zhan et al., 2018)

was imposed on the relatively thick soil layer after the fast dumping. Five dynamic penetration tests (DPT) and four standard penetration tests (SPT) were conducted to show that the fill in the relatively deep layer was also loose. Most of the blow counts for different depth were less than 10, which corresponded to a loose or slightly dense state according to the Chinese standard GB 50021-2001 (2001).

Based on the results of DPT and SPT, the blow counts in the deep layer (greater than 15 or 20 m) show insignificant change with depth, which can be explained by the presence of excess pore water pressure. Evaluations of the degree of consolidation support this observation. The degree of consolidation of the borehole samples can be calculated by the following equation:

$$U = ((e_0 - e))/((e_0 - e_\infty)) \tag{1}$$

where U is the consolidation degree; e_0 is the initial void ratio of the waste material; e is the void ratio of the borehole samples; e_∞ is the void ratio at the completion of consolidation for a given normal stress. The compression curves were measured on the representative CDG samples with two different values of initial dry density. As shown in Figure 2, all data points for the borehole samples are located above the compression curves. The deduced degree of consolidation for the borehole samples covers a wide range from 0% to 91%, and the average degree of consolidation is only 33%. The low degree of consolidation means that parts of the overburden pressure may have been transferred into excess pore-water pressure in the fill at the lower part of the waste dump. The phenomenon of water overflow is observed during the drilling of the boreholes on the sliding bed when they reach a depth of about 18 m.

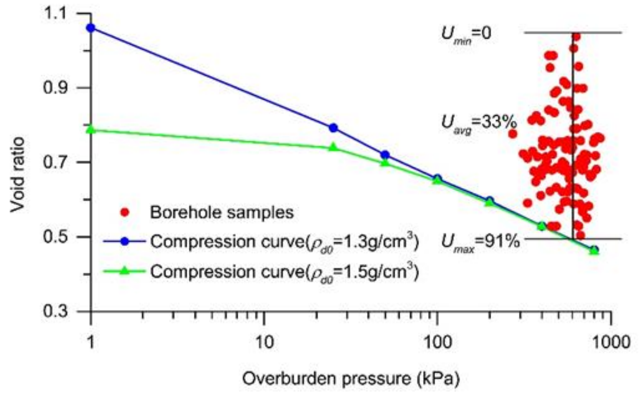


Figure 2. Plot of void ratio versus overburden pressure for the borehole samples in comparison with the compression curves measured on the representative CDG soil samples (Zhan et al., 2018).

3 CENTRIFUGE TESTS

3.1 *Similarity relationship and set up of the model*

Geotechnical centrifuge model tests normally adopt at an n g acceleration, where n is the geometrical scale, to achieve the same stress states of the prototypes in laboratory. For this case, the scaling laws are shown in the second column of Table 1. However, in some cases the prototypes need to be modelled to have a large scale, such as high dam and large slope, so that the model container size and centrifuge capacity are not large enough for an equal-stress modelling of the whole structure. To overcome this limitation in the centrifuge tests, only the main part of the prototype with an equivalent stress (Liu et al., 2005) was modelled. An alternative way is to model the prototype using a geometrical scale (n_l) larger than the gravity scale (n), which yields a reduced-scale unequal-stress centrifuge modelling. Zhang and Hu (1991) and Iai et al. (2005) derived the scaling laws for small-scale modelling based on linear elastic assumption, as shown in the third column of Table 1.

Table 1. Similarity relationship of centrifuge test (prototype: model).

Quantity	Conventional	Reduced-scale
Length	n	n_l
Acceleration	$1/n$	$1/n$
Stress	1	n_l/n
Strain	1	n_l/n
Time (consolidation)	n^2	n_l^2
Displacement	n	n_l^2/n
Stiffness	1	1

Chen et al. (2011) studied a slope and indicates that the equivalent plastic strain and deformation of the reduced-scale model are in good agreement with that of the prototype if $n_l/n \le 3$.

The length of the waste slope in Shenzhen Hongao waste dump is about 600 m which is beyond the size limitation of the ZJU-400 centrifuge in an equal-stress simulation. Therefore, part of the slope in the green dash-line rectangle of Figure 1 was modelled in the experiment, and the reduced-scale similarity relationship was employed. The overall layout of the model is shown in Figure 3. According to the two-unit structure of the prototype (Zhan et al. 2018; Yin et al. 2016), the model was made up of three parts, and the material was collected from the waste dump in Shenzhen. The front part of the lower layer (with height of 13.3 cm) has a dry density of 1.5 g/cm^3 and a low water content of 16%; those of the rear part of the lower layer are 1.4 g/cm^3 and 26% respectively. The upper layer has a dry density of 1.4 g/cm^3 and a low water content of 16%. All the sensors for stress and deformation measurements were placed as shown in Figure 3.

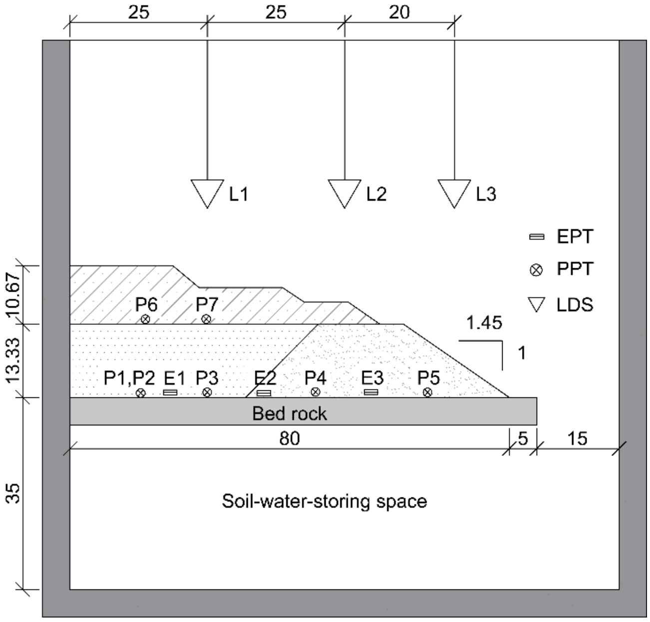


Figure 3. Layout of the model. EPT: earth pressure transducer; PPT: pore pressure transducer; LDS: laser displacement sensor.

3.2 *Test procedures*

The centrifuge test was divided into two stages to simulate the actual filling process of the prototype. In the first stage, the lower layer was filled and accelerated to the acceleration of 150 g as quickly as possible (within 15 minutes). The acceleration was kept for 7 minutes and then decreased progressively to zero. The model container was then taken out from the centrifuge to finish the filling of the upper layer. In the second stage, the complete model was accelerated to 150 g again, which was kept for 19 minutes and then decreased to zero again.

3.3 *Results and analysis*

3.3.1 *Failure process*

The first stage model keeps stable with a slight settlement on the top surface. In the second stage, the upper layer is located above the high water content area, which means an overburden pressure is applied to the wet rear area. With increasing the acceleration, the settlement on the top surface growth progressively, the fill of the upper layer squeezes into the high water content region, and then pushes the front dry material to move horizontally. When the acceleration reaches 140 g, a tensile crack arises on the top surface of the upper layer, and then a landslide occurs.

3.3.2 *Analysis of the results*

Comparison between pre- and post-failure is presented in Figure 4. The dash and solid lines show the outline of the fill before and after the landslide, respectively. A total 6.4 cm settlement is observed at the top surface. The front part show a clear horizontal movement with part of the soil fell into the bottom of the model container. The arrows indicate the displacement of each white mark point. The red line is determined as the failure surface by checking the maximum relative displacement between each layer of the mark point. The failure surface is similar with that of the prototype which is deep-seated into the high water content area and has a gentle inclination.

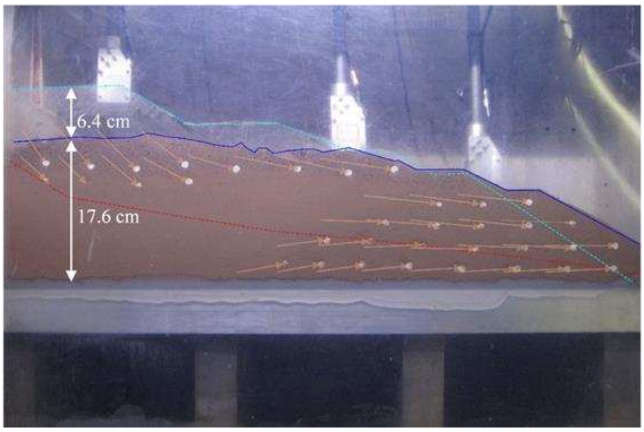


Figure 4. Comparison between pre- and post-failure of the centrifuge test.

In the test, pore water pressures at different locations were measured by the pore pressure transducer as shown in Figure 5. The maximum readings of P1 and P2 were 438 and 330 kPa, respectively. The water level at the rear part of the model was assumed to locate at the top surface of the lower layer for its high water content. Thus, the excess pore water pressures at the locations of P1 and P2 were 238 and 130 kPa, respectively. The excess pore water pressure recorded by P1 kept almost constant when the acceleration was unchanged. In the site of Shenzhen Hongao waste dump, the excess pore water pressure can be observed during the drilling boreholes even it was operated one year after the failure event. The centrifuge test reproduced the failure mode of the prototype and captured the generation of excess pore water pressure in the high water content region.

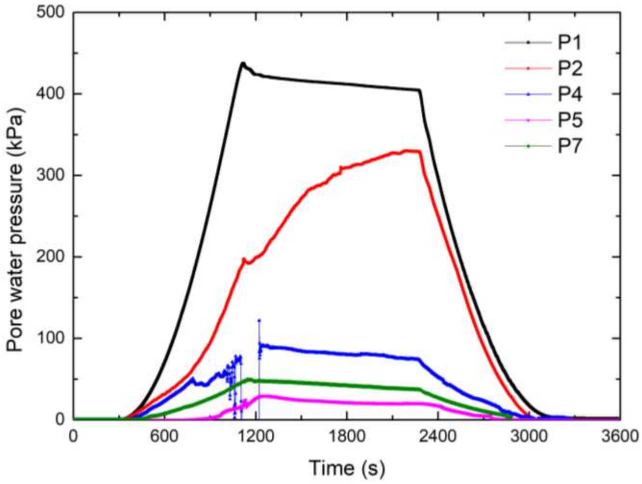


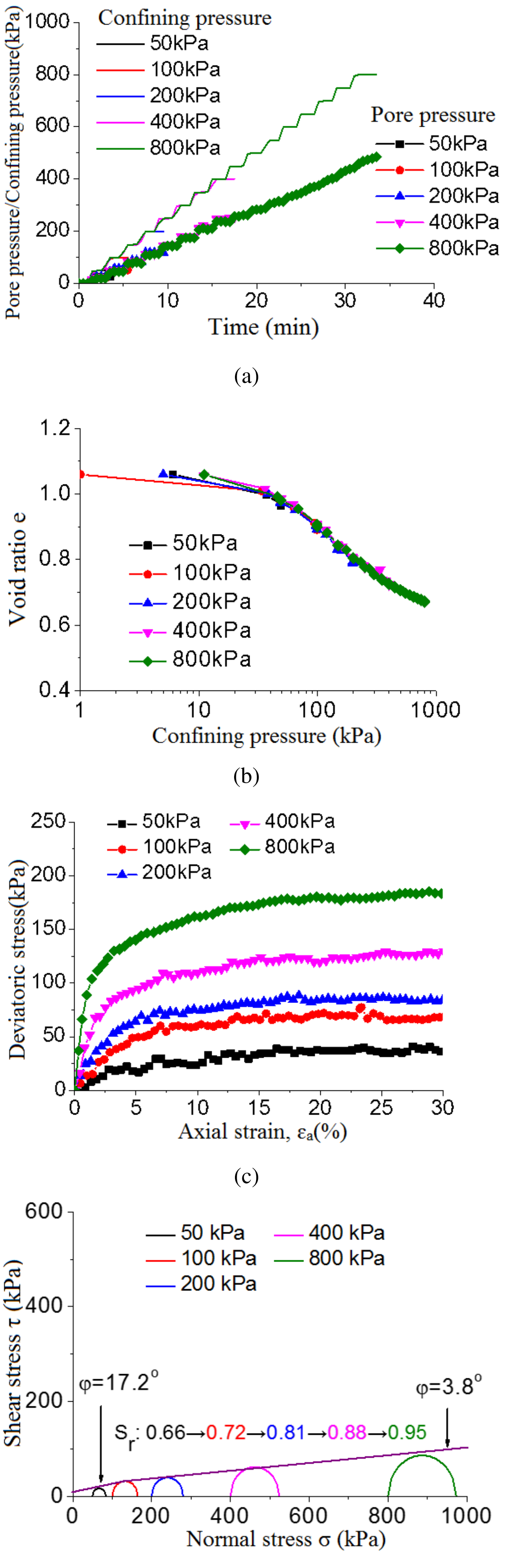
Figure 5. The pore water pressure measured in the second stage of the centrifuge test.

4 SHEAR STRENGTH OF THE FILL MATERIALS WITH UNDRAINED CONDITION

The slope stability is determined by the driving force and shear strength on a potential sliding surface. During the filling process of a slope, the driving force is the component of the fill gravity which is easy to be determined. However, the increase in shear strength in the filling process is normally nonlinear. Using a set of constant strength parameters to simulate the filling process is not reasonable.

Unconsolidated and undrained triaxial tests were carried out to determine the shear strength of CDG samples with a dry density of 1.3 g/cm^3 and different values of water content of 19%, 23% and 26%. Taking the sample with water content of 23% as an example, the test results are presented in Figure 6. The pore pressures show linear dependence on the confining pressure with a pore pressure coefficient of 0.61 in the consolidation stage as shown in Figure 6(a). Although the test was undrained, the pore air was compressed to result in a volume reduction. As indicated in Figure 6(b), a higher confining pressure would yield a greater volume reduction, suggesting a greater increase in degree of saturation. The stress-strain curves and Mohr's circles of the compressed samples are presented in Figure 6(c) and 6(d).

The shear strength of the CDG samples with water content of 23% shows a clear nonlinear trend with confining pressure. As stated earlier, a higher confining pressure corresponds to a higher degree of saturation when the isotropic compression is complete. As shown in Figure 6(d), when the degree of saturation after compression exceeded a threshold (about 0.7 in this study), the friction angle shows a distinct reduction. The soil with a higher initial degree of saturation needs a lower confining pressure to reach this threshold. In the case of Shenzhen landslide having a two-unit structure, the driving force of a specific position grows almost linearly while the shear strength increases with friction angle gradually decreasing. When the landfilling reaches a critical height, the driving force exceeds the shear strength in the high-water-content zone first. This mechanism is supported by the observation that a clear settlement was first occurred at the rear part with high water content in the centrifuge test. The fill at the front was then pushed out. The strength parameters of the CDG samples with different water contents are listed in Table 2. The total stress friction angles of the samples with water content of 23% and 26% are only 3.8° and 3.4°, respectively, which are less than the inclination of the slip surface (6°). This explains the deep-seated slip surface and gentle inclination in the Shenzhen landslide.



(a)

(b)

(c)

(d)

Figure 6. UU test results of CDG samples with water content of 23%: (a) confining pressure and pore pressure vs time, (b) void ratio vs confining pressure in the isotropic compression stage; (c) deviatoric stress vs axial strain and (d) shear strength envelope in the shear stage.

Table 2. Strength parameters for the CDG samples with different water content.

Water content (%)	Shear strength parameters			
	φ_1(°)	c_1(kPa)	φ_2(°)	c_2(kPa)
19	17.2	11	8.3	80
23	17.2	0	3.8	27
26	-	-	3.4	18

5 STABILITY ANALYSIS BASED ON THE TOTAL STRESS METHOD

Stability analysis by limit equilibrium method is carried out to verify the proposed failure mechanism. By following the two units structure stated before, the calculation model is made up of three parts with different water content W_0; the rear wet area is divided into a high water content area (W_0 = 26%) and a transition area (W_0= 23%). The parameters listed in Table 2 are employed for the analysis of total stress. Bilinear model is used for the low water content area (W_0= 19%) and the transition area. As shown in Figure 7, the lowest safety factor is 0.83 with a sliding surface passes though the high water content area and has an exit point close to the terrace T3. It forms a deep-seated landslide consistent with the site investigation results. The stability analysis using undrained strength parameters can predict the failure and failure mode correctly. It means, in the real landfilling process with a fast rate, water in the waste dump is difficult to drain.

6 LESSONS LEARNT FROM THE LANDSLIDE AND FUTURE WORK

Based on more than the study for two years, the lessons learned from the Shenzhen landslide are summarized as below:

1. High water content fine-grained soil generated excess pore water pressure during the fast filling process since water was difficult to drain; the undrained shear strength shows a nonlinear increase with overburden pressure, which may lead to a deep-seated failure.
2. The absence of interception and drainage facilities has led to the rise of groundwater table in the waste dump, and this then triggered a failure in lower layer of the slope.
3. Loose fill with high water content shows volume reduction during shearing, which may hence result in static liquefaction. It further yields fluid-like flow with a long run-out distance. Such landslide normally causes catastrophic results due to the fast speed and long distance.

In view of the above understandings, the following measures are proposed with the purpose to prevent this kind of disaster from happening again.

1. Excess pore water pressure is an unfavorable factor for slope stability. There are three ways to avoid slope failure. One way is to focus on the material and try to reduce the water content by drying. However, it is difficult to be operated since there is not enough space for drying a large volume of wet construction waste. Another way is to control the filling rate under a critical value. This value could be obtained by effective stress analysis of stability. Different filling rate yields different excess pore water pressure in consolidation analysis by the finite element method. The excess pore water pressure is then import into the effective stress analysis of stability to get a corresponded safety factor. The filling rate corresponding to the control safety factor, such as 1.2, is the critical value needed to be determined. The third way is to develop the expressions of the undrained shear strength and use it in the total stress analysis of slope stability to determine the allowed height of the landfill as the standard of stability control.
2. A guideline or code is needed to regulate the design and construction of the interception and drainage facilities in a waste dump. Both surface runoff and underground seepage must be collected and discharged outside the dump field. In addition, the monitoring of underground water level is necessary.

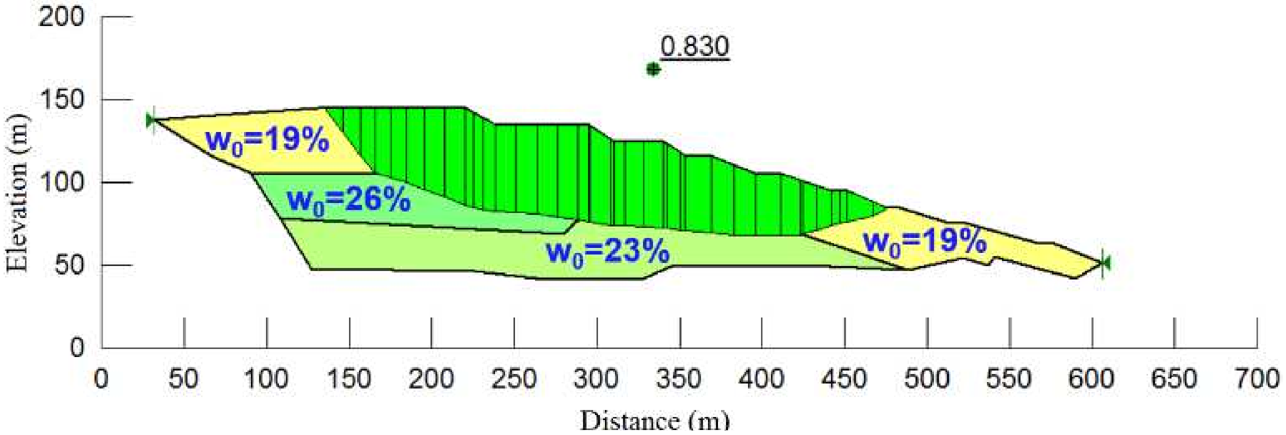


Figure 7. The stability analysis result of Shenzhen Hongao waste dump.

3. The former mentioned guideline or code should also involve the item about compaction operation. After dumping, each layer should be well compacted to a specific compactness, such as 90%. At the same time, the water pressure should be monitored.
4. The measures for maximizing capacity in the construction stage should be studied. The plastic drainage board can be used to accelerate drainage consolidation. Geosynthetic reinforcement can enhance the shear strength and limit the volume changing of the fill. The capacity depends on the allowed filling height. For the fill with multiple units, the maximum height corresponding to a given slope ratio and width of the low water content area will be determined by stability analysis. The maximum capacity will be determined by comparing the results for different pairs of slope ratio and width of the low-water-content area.

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