Numerical analysis of dynamic characteristics of sludge-type slag landfill landslide

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Abstract: The Artificial landfill landslide in Guangming District, Shenzhen, which occurred on December 20, 2015, showed the same characteristics as mudflow after sliding, which had long sliding movement distance and large coverage area, and caused serious casualties and property losses. Therefore, research on the dynamic characteristics of artificial accumulation landslide is of great significance for landfill slope hazard assessment and prevention in urban construction. On the basis of detailed collection of landslide investigation data and field investigation, the motion of the landslide was simulated with the friction rheological model by the software DAN-W in this paper, in order to obtain the characteristic parameters of landslide movement. The results showed that, the maximum movement distance was 1,112 meters and a running time of 105s simulated by friction model. The maximum front velocity was 22.5m/s and occurred at a horizontal distance of 632 meters. The horizontal length of the accumulation mass was 580 meters and the average thickness was about 8.2m. The numerical simulation results are basically consistent with the field survey results. The simulation model and the motion characteristic parameters of the muck can be used as reference for the prevention and control design of slope of similar muck field.

1. Introduction

A catastrophic landslide happened in Guangming District, Shenzhen, Guangdong province On December 20, 2015, which is caused by artificial accumulation slope, and had inflicted heavy casualties and property losses[1-2]. The accumulation form after sliding shows the similar characteristics as mudflow. This type of landslide often has long sliding distance, wide covering area and can be extremely destructive[3-6]. Since the 1980s, many landslide disasters caused by artificial debris accumulation have occurred frequently in many parts of the world due to the imperfect risk management of artificial debris slope[7-8]. In 1988, lateral sliding failure occurred in the Kettleman Mountain landfill site in California, USA. It took a lot of effort to finish the repair work[9]. On 10 July 2000, the slope of the Philippa Payatas muck farm was destabilized, resulting in the death of at least 330 people and the damage to a large number of buildings due to extremely heavy rainfall[10]. On 21 February 2005, the Leuwigajah landslide slope in Indonesia was destabilized by heavy rainfall, sliding for a distance of 1 km and causing more
than 100 deaths\cite{11}. The stability of the slope of muck accumulation body is strongly affected by human engineering activities, and its instability is usually unanticipated, and occurs in urban densely populated areas of large scale and causes serious damage\cite{12}.

With the comprehensive development of hydropower projects, high-speed railways, urban fast roads and other infrastructure projects in China, more and more construction waste will be discharged into the nature, which will have a more and more strong impact on the geological environment\cite{13}. Many catastrophic landslide events show that the study on the design, treatment and monitoring of artificial landfill slope is in urgent need of further development, and the instability mechanism and movement mechanism of accumulation landslide are also in urgent need of in-depth research. Empirical formula method, numerical simulation and physical model test are three common methods which are used to study the motion characteristics of landslide after instability\cite{14-18}.

Since the calculation results can provide relatively complete and systematic information and can greatly save cost and time, in recent years the numerical simulation method has been increasingly used in the back analysis of landslide movement or hazard prediction\cite{19-23}. The numerical simulation method can reflect the internal deformation mechanism and the variation characteristics of related mechanical properties very well in the process of landslide run-out progress.

Many scholars at home and abroad have carried out numerical simulation research on the run-out characteristics of sludge-type landslide from different angles, and have drawn many useful conclusions. Begueria et al. considered complex terrain conditions and used two-dimensional finite difference method to solve the motion equation of fluid continuum. Based on GIS environment, Massmov2D software was developed and applied to inverse calculation of movement range and accumulation thickness of debris flow cases that have already occurred\cite{24}. Wang et al. considered the influence of deformation work and internal energy dissipation on debris flow dynamics and proposed a landslide dynamic analysis model based on energy conservation. Lagrange finite difference method was used to solve the governing equation in the model, and can be well applied to the simulation of the motion characteristics of landslide and debris flow\cite{25}. Utili et al. simulated the motion characteristics of dry particle flow generated by column collapse through discrete element method, and analyzed the influence of length-width ratio of column and internal particle friction on particle collapse motion characteristics\cite{26}. By using discrete element numerical simulation, Chai et al. (2001) analyzed the whole process of the movement of Yigong landslide in Tibet in 2000, and analyzed the movement mechanism of the vibration of the collapse body that caused the gully slope sediments sand soil to liquefy and further promoted the formation of high-speed debris flow\cite{27}. Considering the erosion rate, Du et al. (2015) developed a numerical model based on the finite volume method, and conducted an inversion analysis of movement process of the El Picacho landslide by selecting the Voellmy rheological model\cite{28}. Gao et al. (2018) carried out a numerical simulation of the whole run-out process of the long-runout landslide Jiweishan Landslide considering erosion effect, and made comparison the parameters of landslide accumulation, erosion area and run distance with the field investigation\cite{29}. Yang et al. (2018) used Rapid model and "equivalent fluid" dynamic model to simulate the characteristics of the Kalayagaqi Landslide in Yining County, Xinjiang, and obtained the characteristic parameters such as run duration, run speed\cite{30}. Ouyang Chaojun et al. developed a sliding dynamic analysis model MassFlow based on the MacCormack-TVD finite difference method and applied it to the analysis of motion characteristics of classic dam burst and landslide cases\cite{31-32}. From the above studies, it can be seen that the numerical simulation studies on the motion characteristics of mudflow landslide are mainly based on the continuum model and discrete element model, while few studies have been carried out on the motion characteristics of artificial accumulation body, and the study on the instability and motion mechanism of landslide is not in-depth enough.

Based on the detailed information collection and landslide surveying and mapping, using the two-dimensional model of finite element numerical simulation, this work establish landslide numerical model and used friction rheological model, the characteristics of sludge-type landslide are analyzed, and the parameters such as velocity distribution, accumulation body thickness distribution and movement range are obtained, in order to provide a reference for similar landslide hazard prediction and prevention.
2. Brief of the landfill landslide

2.1. Engineering geological conditions of landslide area

The landfill site was originally an abandoned mine pit and was later transformed into a storage site. It is located halfway up the mountain, surrounded by mountains on three sides and in a "calabash shape". The outlet faces north, facing the industrial estate below.

The highest elevation is about 300m and the lowest is about 35m. Due to the lack of drainage facilities, large amounts of water from precipitation existed in the mine before the landfill. The strata structure in the landslide area is generally divided into three layers from top to bottom. The upper layer is the slag discharge field landfill, and the composition is mainly the weathered soil of granite, sandstone and other strata, clay and domestic construction garbage. The soil is loose and the composition is mixed, and the bottom of the landfill has a high water content[2]. In the middle part, the abandoned quarry soil was mainly composed of clay soil, gravel and granite breccia. The bottom and surrounding rock are granite with poor permeability. The rock was moderately weathered and fissures are well developed in the surface. The average annual precipitation in the region is 1605mm, and there is no large-scale rainfall before and after the landslide[2].

The main engineering activities affecting the slope stability of muck field are muck filling[2]. The residual soil is constructed from north to south and from low to high terrace landfills. About one step is set for every 10m, which is divided into 9 steps[2]. According to the field survey data, the top elevation of the sliding source area landfill is about 160m, and the bottom elevation is about 65m. Before the slope failure, T1~T6 steps have been filled and compacted, T7 and other steps are still under construction, and the overall slope angle of the residual soil field is about 20º (Fig 1). Before the landslide occurred in December 2015, the total volume of landfills was about 580×10^6m^3.

![Fig.1 Cross-section diagram of Shenzhen landfill landslide](image)

2.2. Analysis of the slope instability mechanism

The landslide is mainly caused by the liquefaction under the interaction of water and landfill. The water in the residue field mainly comes from atmospheric precipitation, residual water in abandoned mines, water contained in the residue soil itself and the infiltration of spring from the surface of the mountain behind. There was a large amount of water in the mining pit, which had not been completely discharged before landfill. In addition, there was no complete bottom and slope drainage facilities set in the residue soil field, which leads to surface water infiltration downward. The water content of the slope soil increased and underground water level rise gradually with the increase of filling. Therefore, the excess pore pressure at the front of the slope increased gradually. With the rapid and continuous loading of residual soil at the rear edge, the pore water pressure increases continuously, the effective stress between soil particles decreases gradually, and the strength of soil below the ground water level decreases. Then it causes the settlement of soil above the ground water level and forms the soft soil zone. The process of quickly and directionally applying soil loads is similar to the process of undrained shear test on the underlying soil. When the underground water level gradually rises to the elevation of the lower pass of the quarry pit, and the area of the boundary zone between the upper filling soil and the lower argillite
soil reaches the critical value, which eventually leads to the instability of the landfill soil and the overall sliding.

2.3. Accumulation characteristics of the slope failure

The landslide area can be divided into three areas, which are the source area, the accumulation area and the circulation area (Fig. 2). The north-south length of the area is about 370m, the east-west width is about 400m, and the area is about 0.12km². By comparing the topographic lines before and after sliding in the landslide profile, it can be seen that the sliding surface is mainly located in the artificial fill in the muck field. The average thickness of the sliding body is about 30m, and the volume is about $2.5 \times 10^6$ m³. The dip Angle of the sliding surface is small, about 4°. After the sludges, the slippage accelerates rapidly, and finally the movement stops and accumulates in the industrial estate under the slope. The total length of the slide is about 1100m, and the equivalent friction angle is about 6°, which belongs to the low-angle slide[1].

![Plan view of Shenzhen landfill landslide](image)

The largest width of the accumulation area is about 630m, the circulation area is at the "gourd mouth", and the narrowest and the width at narrowest place is about 150m. The accumulation area is about 0.38 km², and the total volume is about $2.75 \times 10^6$ m³ (Fig. 1).

The total length of the landslide from the back edge of the muck field to the front edge of the accumulation body is 1100m. The landslide accumulation area is mainly located in the north of T1 step of the construction waste residue landfill with a length of 726m, an east-west width of 150~630m and an average thickness of about 10m. The volume is about $2.73 \times 10^6$ m³, and the main compositions are construction waste and residual sludge.

3. DAN-W analytical method

O. Hungr proposed the 'equivalent fluid' hypothesis in 1995. He believed that complex detrital fluid movements could be regarded as ideal fluids and developed methods for analyzing the relationship between internal deformation and resistance of detrital flows[33]. DAN-W (Dynamic Analysis) is a tool to analyze the characteristics of landslide motion by taking landslide as "equivalent fluid". Based on the actual investigation and the accurate analysis of the instability and failure mechanism, a generalized
landslide mechanical model was established, the landslide movement path was set up, and the appropriate rheological calculation model was selected to simulate the movement process of the landslide, the parameters such as run duration, run distance, velocity distribution, volume vibration of accumulation body and thickness distribution are calculated. The basic principle is that the landslide body is first divided into N blocks. By establishing the mechanical balance equation and motion equation, the mechanical analysis is carried out for each block. The finite difference method is adopted to solve the equation, and finally the accumulation range, run velocity, run distance and other indexes of the landslide are calculated [33].

The characteristics of landslide movement induced by natural factors or human activities are complex and affected by soil moisture, landslide scale, topography effect and other factors. At present, the research carried out by the "equivalent liquid" method is mainly used on back analysis of the characteristics of movement of the occurred landslides. Through the analysis of parameters of many known landslide, such as sliding distance, accumulation thickness, sliding time and sliding velocity, the most suitable rheological model and parameters can be analyzed, and then it can be used for the prediction of landslide movement mechanism and characteristic parameters, so as to provide reference basis for the hazard zonation of similar landslides [34-35].

When DAN analysis method is used, the selection of rheological model is particularly important, because there is a close relationship between the basement resistance and the rheological characteristics of the landslide, which has a great impact on whether the simulated landslide can be and accurately reflect the real landslide. Frictional model, Voellmy model and Bingham model are widely used to analyze the rheological characteristics of landslide mass [36-37].

The results of a large number of simulation experiments show that the frictional rheological model is suitable for calculating the base frictional resistance of granular materials and can reflect the movement characteristics of landslides very well. In the friction model, the resistance $T$ is assumed to be a function of the effective normal stress acting on the base, and the function that affects the value of $T$ is expressed as:

$$T = A_f H (\cos \alpha + \frac{\omega}{g}) (1 - r_w) \tan \varphi \quad (1)$$

Where: $T$ is the base resistance; $H$ is the depth of the sliding body; $\alpha$ is the slope angle of the slope; $\gamma$ is the unit severity of slippage; $\omega$ is the centrifugal acceleration related to the motion path; $\varphi$ is the friction angle; $r_w$ is the pore water pressure coefficient.

4. Numerical model and parameter selection
According to the profile of the Shenzhen landslide, by analyzing and comparing the slope morphology before and after sliding, the movement path of the landslide, the slope before sliding, the original terrain and the shape of the source area of accumulation body can be obtained. Based on the field survey, the average width data of landslide source area in was obtained, and the whole landslide model was divided into 160 equal volume units, thus the dynamic analysis model of landslide was established in the DAN-W software (Fig. 3).

Fig.3 DAN model of the landslide in Guangming New District of Shenzhen city
Considering that the material composition of the debris body of Shenzhen landslide is mainly weathered soil, clay and construction waste, etc., the soil body is relatively loose and will be broken and disintegrated soon after the instability slips out from the sliding source area, Frictional model is selected
for analysis in this work. Since the shape of the landslide will have a certain influence on its motion speed, motion distance and other characteristics, but the value of the shape coefficient in the model will not change with the position of the motion path, Therefore, according to the accumulation characteristics of the landslide body after sliding, the entire cross section of the landslide can be equivalent to a rectangle, and the shape coefficient can be set as 1. The average weight of each step of the soil in the residue field was 18.5 kN/m³, which is set as the weight value of the slide body, and the scraping effect was not considered in the analysis. The physical and mechanical parameters of soil mass used in the numerical simulation are shown in Table 1.

| Parameters used in the simulation of landslide movement |
|--------------------------------------------------------|
| Rheological model | unit weight (kN·m⁻³) | frictional angle (°) | pressure coefficient | erosion depth /m |
| Friction model    | 18.5                 | 20                   | 0.10                | 0               |

5. Results of numerical simulation

(1) The velocity of the observation point varies with time

According to the characteristics of Shenzhen landslide, two observation points (A and B) was set at 650m and at 1000m respectively, and the change curve of velocity with time was obtained (Fig. 4).

![Fig.4 Relation curves of velocity varies with time at the 650m and 1000m observation points](image)

From the image, it can be seen that the accumulation velocity of the landslide increases gradually at the observation point of 650m and reaches a maximum velocity of 22.5m/s at 22s, and then the sliding velocity begins to slow down. The maximum velocity at the observation point of 1000m reached 17.8m/s at 21.35s, and then the velocity decreased linearly, and finally stopped sliding at 85s.

(2) Variation of thickness with time at the observation point

![Fig.5 Relation curves of thickness varies with time at the 650m and 1000m observation points](image)

Two observation points were also set at the horizontal distance of 650m and 1000m respectively in order to obtain the variation of thickness with time (Fig. 5). It can be seen from the image that the maximum accumulation thickness reaches 15.2m at the observation point of 650m at the time of 76s, and the maximum accumulation thickness reaches 3.8m at the observation point of 1000m is 19.5m.
The average thickness of the accumulation body is about 8.2 m, which is smaller than the thickness obtained from the field investigation.

3) The relationship between the velocity of the leading edge and trailing edge with time

Through simulation, the relation curves of the velocity of leading edge and the trailing edge and the maximum velocity of the sliding body with time change are obtained (Fig. 6). From the chart, it can be seen that the edge and trailing edge of the sliding body start almost at the same time, the front movement speed faster, after reaching maximum speed at 12.5s, movement speed drops rapidly, the speed of the leading edge dropped to 0 at 57s, and local area in the central of sliding body still run at low speed, this is caused by the internal adjustment of the slide body with the change of terrain during the movement. The maximum velocity of the landslide is 22.5 m/s. It is located at the horizontal distance of 632 m in the movement path of the landslide at 19.5 s after the landslide starts to sliding.

![Relation curves of front and rear velocity varies with time](image)

Fig. 6 Relation curves of front and rear velocity varies with time

4) Variation of run distance and motion form of sliding body

By analyzing the numerical calculation results of DAN-W, it can be concluded that the maximum movement distance of the landslide is 1112 m. It can be seen from the morphology of the filled earth on the sliding surface at different moments during the landslide movement that the morphology of the slime body changes greatly in the early stage of the movement, while the slime body moves slowly in the late stage of the movement and the morphology changes slightly (Fig. 7). As can be seen from the figure, there are still a large amount of residual soil in the pit in the source area after sliding, which is consistent with the field investigation.

![Profiles of sliding mass at different times](image)

Fig. 7 Profiles of sliding mass at different times

6. Conclusion

In this work, based on the continuum model, the run-out characteristic of the artificial accumulation landslide of sludge-type is studied. The brief of slope failure case of the Guangming District Landslide in Shenzhen and the environment geological conditions including its lithological characteristics and formation mechanism were analyzed.

On the basis of acquisition of the terrain and subsurface strata and structure in the landslide area before and after sliding, the two-dimensional numerical model is established in DAN-W, and the run-out characters of landslide movement are researched. The main conclusions are as follows:
The soil mass of the Shenzhen Landslide is mainly artificial landfill, and groundwater is one of the important factors that lead to the instability of the accumulation slope. The continuous overquick and overloading of residual soil lead to the consequence that the pore water pressure at the bottom of fill soil can’t dissipate timely and the ground water level increased incessantly, which ultimately leads to the overall instability of the landfill slope and cause the serious disaster.

The process of migration and accumulation of sliding body was simulated by using DAN-W software without considering the erosion effect. The simulation results showed that the run distance of the fill soil was 1112m, which took about 105s, and the maximum velocity of the sliding body was 22.5m/s, which occurred at the horizontal distance of 632m. The average thickness of the landslide accumulation body is about 8.2m and the horizontal length of the accumulation area is about 580m.

The model and parameters obtained in this work can be used as references for slope design and hazard prediction of similar slope.

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