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Mechanism of the December 2015 Catastrophic Landslide at the Shenzhen Landfill and Controlling Geotechnical Risks of Urbanization

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ABSTRACT

This paper presents findings from an investigation of the large-scale construction solid waste (CSW) landslide that occurred at a landfill at Shenzhen, Guangdong, China, on December 20, 2015, and which killed 77 people and destroyed 33 houses. The landslide involved 2.73×10^6 m^3 of CSW and affected an area about 1100 m in length and 630 m in maximum width, making it the largest landfill landslide in the world. The investigation of this disaster used a combination of unmanned aerial vehicle surveillance and multistage remote-sensing images to reveal the increasing volume of waste in the landfill and the shifting shape of the landfill slope for nearly two years before the landslide took place, beginning with the creation of the CSW landfill in March, 2014, that resulted in the uncertain conditions of the landfill's boundaries and the unstable state of the hydrologic performance. As a result, applying conventional stability analysis methods used for natural landslides to this case would be difficult. In order to analyze this disaster, we took a multistage modeling technique to analyze the varied characteristics of the landfill slope's structure at various stages of CSW dumping and used the non-steady flow theory to explain the groundwater seepage problem. The investigation showed that the landfill could be divided into two units based on the moisture in the land: ① a front uint, consisted of the landfill slope, which had low water content; and ② a rear unit, consisted of fresh waste, which had a high water content. This structure caused two effects—surface-water infiltration and consolidation seepage that triggered the landslide in the landfill. Surface-water infiltration induced a gradual increase in pore water pressure head, or piezometric head, in the front slope because the infiltrating position rose as the volume of waste placement increased. Consolidation seepage led to higher excess pore water pressures as the loading of waste increased. We also investigated the post-failure soil dynamics parameters of the landslide deposit using cone penetration, triaxial, and ring-shear tests in order to simulate the characteristics of a flowing slide with a long run-out due to the liquefaction effect. Finally, we conclude the paper with lessons from the tens of catastrophic landslides of municipal solid waste around the world and discuss how to better manage the geotechnical risks of urbanization.

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1. Introduction

On December 20, 2015, a large landslide occurred at the Hong'ao Village construction solid waste (CSW) landfill in the Guangming New District of Shenzhen, Guangdong, China (103°33′48″E, 30°54′55″N) (Fig. 1). The landslide involved 2.73 × 10^6 m^3 of CSW, and had a length of about 1100 m, making it the largest landfill slope failure in the world. Because the landslide killed 77 people and destroyed 33 houses within an industrial zone of Shenzhen, the State Council of China immediately organized an investigation team to look into the causes of the landslide. The lead author of this paper was the head of the expert group within this investigation team; the second to eighth authors were also group members; and the ninth and tenth authors participated in the remote-sensing and field investigation. The authors collectively produced the cause-analysis report to the State Council of China and prepared this paper based on the field investigation, unmanned aerial vehicle (UAV) drone 3D photogrammetry, the dynamic analysis of multistage remote-sensing images, *in situ* and laboratory physical-mechanics tests, computer simulation, relevant archives, and witness interviews.

Many municipal solid waste (MSW) landfill landslides have occurred around the world in recent decades due to unsound geotechnical engineering risk controls and practices, revealing the importance of site selection, construction, and operation [1]. For example, on July 10, 2000, a waste landslide with a volume of 16 000 m^3 occurred in the Payatas landfill in Quezon City, the Philippines, after two weeks of heavy rain from two typhoons. That event killed at least 330 people and left many homeless, and had one of the worst death tolls of all landfill landslides [2,3]. On February 21, 2005, a catastrophic waste landslide with a volume of 2.7 × 10^6 m^3 occurred at the Leuwigajah dump site in Bandung, Indonesia, due to heavy rainfalls [4]. This disaster caused 147 deaths and, along with the Shenzhen landslide, was one of the largest landfill landslides to date in terms of the volume of waste involved. With increasing volume of waste and constant changes in a landfill slope's structures, the physical and mechanical properties and the hydrologic performance of a given landfill change over time. Therefore, in contrast to natural landslide analysis, the study of landfill slope failures must apply a dynamic analysis that probes into boundary conditions and stability. For this landslide investigation, we adopted a multistage modeling technique to study the influence of soil mass structure and hydrologic performance changes on the stability of landfill landslide during different phases of placement. The dynamics of rapid long run-out sliding triggered by liquefaction after slope failure was simulated with LS-RAPID software. Finally, taking typical landfill landslides worldwide into consideration, this paper discusses the geotechnical risk controls of urbanization.

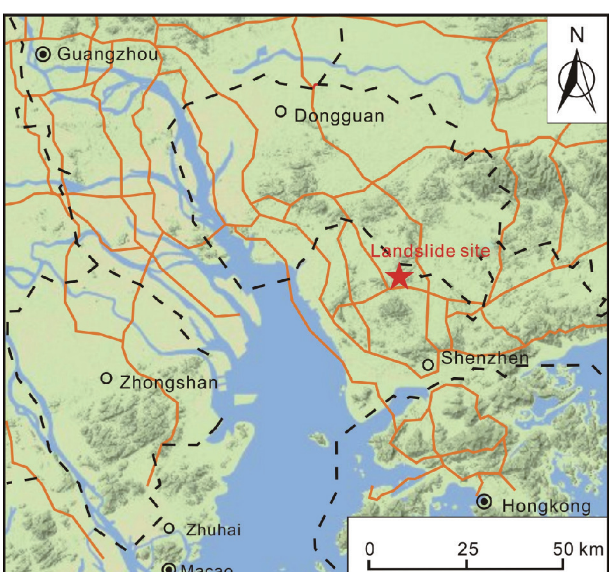

Fig. 1. Location of the December 20, 2015 landslide at the construction solid waste (CSW) landfill in Guangming New District of Shenzhen, Guangdong,

2. Basic features of the landfill and landslide

2.1. Geological conditions

The Shenzhen landfill is located at the foot of the northern side of Dayan Mountain, inside the Guangming New District of Shenzhen. The southern elevation of Dayan Mountain is 306.8 m. A valley with a lowest elevation of 34 m is situated on the northern side of the mountain. The original location was an abandoned open pit. According to a satellite remote-sensing image from December 2013, shown in Fig. 2(a), the pit spread toward the south and north, was surrounded by the mountain on the east, west, and south, and narrowed down at the north. The exposed bedrock of this site is composed of strongly, moderately, and slightly weathered granite, which develops into three prominent and distinctive planes with altitudes of 15°–25°∠75°–84°, 265°–270°∠48°–58°, and 210°–225°∠40°–85°, respectively. The surrounding rock mass provides the landfill with a high degree of stability. There are two types of groundwater under the surrounding rock mass, including fissure water in the block rock mass and pore water in the surface weathered granite regolith.

2.2. Landfill slope of construction solid waste (CSW)

According to remote-sensing images taken two days before the landslide (Fig. 2(b), taken on December 18, 2015) and to the field investigation, the elevation of the back edge of the landfill was 160 m, and the elevation of the front edge of the bottom, consisting of boulder and gravel, was 46.1 m. Out of 10 terraces, terraces T0 to T6 had been compacted, shaped, and afforested, and terraces T7, T8, and T9 were being filled and compacted with a preliminary shape (Table 1). The general angle of the landfill slope downwards had a slope ratio of 1∶2.5 (Fig. 3). The surface of the edge slope was covered with grass and with non-woven fabrics that were meant to mitigate rainfall and liquid from seeping into the landfill.

2.3. Zoning of the landslide

The impact area of this landslide was 0.38 km^2, with a length of 1100 m from south to north and a width ranging from 150–630 m. The total volume of waste in the landslide was 2.73 × 10^6 m^3; this volume could be divided into two zones based on how much groundwater seepage was in the ground beneath the waste (Figs. 4 and 5).

2.3.1. Source area of landslide

Based on a comparison of remote-sensing images from December 18, 2015 with digital elevation model (DEM) data from December 30, 2013 (before the construction of the landfill), the landfill had a volume of about 5.83 × 10^6 m^3 CSW before sliding. On the afternoon of December 21, 2015, the day after sliding, a UAV drone took aerial photos, shown in Fig. 2(c). The source