Geomorphology 228 (2015) 746–755

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Can the collapse of a fly ash heap develop into an air-fluidized flow? — Reanalysis of the Jupille accident (1961)

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ARTICLE INFO

Article history:
Received 11 June 2013
Received in revised form 24 January 2014
Accepted 28 January 2014
Available online 12 February 2014

Keywords:
Landslide
Fluidization
Numerical modeling
Fly ash

ABSTRACT

A fly ash heap collapse occurred in Jupille (Liege, Belgium) in 1961. The subsequent flow of fly ash reached a surprisingly long runout and had catastrophic consequences. Its unprecedented degree of fluidization attracted scientific attention. As drillings and direct observations revealed no water-saturated zone at the base of the deposits, scientists assumed an air-fluidization mechanism, which appeared consistent with the properties of the material. In this paper, the air-fluidization assumption is tested based on two-dimensional numerical simulations. The numerical model has been developed so as to focus on the most prominent processes governing the flow, with parameters constrained by their physical interpretation. Results are compared to accurate field observations and are presented for different stages in the model enhancement, so as to provide a base for a discussion of the relative influence of pore pressure dissipation and pore pressure generation. These results show that the apparently high diffusion coefficient that characterizes the dissipation of air pore pressures is in fact sufficiently low for an important degree of fluidization to be maintained during a flow of hundreds of meters.

1. Introduction

Fly ash is a residue of the combustion of coal in thermal power plants. During decades, it used to be piled up onto heaps reaching heights of tens of meters. However, not enough attention was paid to the stability of these heaps (Bishop, 1973). Because of insufficient compaction, absence of a drainage system, or inadequate site choice, several fly ash heaps collapsed in the past. Nowadays, several fly ash heaps still require careful monitoring as they threaten the inhabited areas.

Predicting the spatial extent, depth of deposits, and propagation time of such sliding events is of particular relevance in a risk management perspective. For this purpose, numerical models can take advantage of the vast body of knowledge available in the field of landslide modeling. However, a catastrophic event of that kind, which took place in Jupille (Liege, Belgium) in 1961 and which has been carefully documented by contemporary authors (Albrecht et al., 1961; Calembert and Dantinne, 1964), raise a still unresolved question: can the distinctive properties of fly ash (particle fineness, potential high porosity) promote a distinctive fluidization mechanism?

Over the past decades, several kinds of landslides have been described as being astonishingly mobile, such as sturzstrome (Hsü, 1975) and pyroclastic flows (Hayashi and Self, 1992). Although questionable (Legros, 2002), a widespread indicator of mobility for landslides is the ratio of fall height H_{CM} to distance L_{CM} traveled by the center of mass of their deposits. This ratio is compared to the friction angle of the material so as to highlight the degree of fluidization of the landslide. The decrease of the H_{CM}/L_{CM} ratio with the volume of the landslide is a well-established and universal trend that underlines a universal mechanism behind such different landslide events (Hayashi and Self, 1992; Legros, 2002). Compared to data available in literature, the uniqueness of the fly ash flow in Jupille (1961) is emphasized by its low H_{CM}/L_{CM} ratio despite a relatively low volume of displaced material (as detailed in Section 3). To our knowledge, it is the only accident of that type reported in scientific literature. As such, it provides a valuable and unique input to the scientific discussion on the mechanism of these mass movements.

Calembert and Dantinne's investigation of the fly ash heap collapse (Calembert and Dantinne, 1964) led them to assume that an air-fluidization mechanism was the reason for the high mobility of the flow in the absence of any water-saturated layer in its deposits. Bishop (1973) followed their interpretation. Nowadays, fluidization by air is no longer accepted as a general mechanism to explain the mobility of nonsaturated landslides (Legros, 2002). However, it remains a relevant mechanism to explain the mobility of pyroclastic flows, i.e., flows of dense mixtures of volcanic gas and particles (Roche et al., 2010; Roche, 2012).

As Calembert and Dantinne (1964) have identified a possible process that could have triggered a relative motion between the fly ash particles and the important amount of interstitial air, we test here this air-fluidization assumption using a two-dimensional numerical model that aims at reproducing the location of the deposits following the Jupille 1961 fly ash heap collapse. Air-fluidization is postulated in the model and simulations have been conducted to verify whether the dynamic

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http://dx.doi.org/10.1016/j.geomorph.2014.01.020

pore pressures can persist long enough to enable a flow of hundreds of meters.

This paper starts with a comprehensive description of the accident (Section 2) so that the available data can be used as a new benchmark to validate numerical models. The phenomenon is then discussed based on information from literature (Section 3). Section 4 details the numerical model used to simulate the flow, while the results are presented and discussed in Section 5. Finally, the Conclusion section emphasizes that the possibility of an air-fluidization phenomenon should not be disregarded in risk analyses dealing with fly ash heap failures.

2. Case study

In the late 1950s, fly ash produced by a thermal power plant was heaped up at the head of a narrow valley in Jupille (Liege, Belgium). The heap reached a height of 29 m and extended over an area of 4 ha. On 3 February 1961, approximately one-third of the 600,000 tons of ash collapsed and flew on a distance of about 700 m within about a minute. The flow destroyed numerous houses and led to several casualties.

Descriptions of the heap and the deposits left by the flow, as well as measurements of the physical and mechanical properties of the material can be found in papers by Albrecht et al. (1961) and Calembert and Dantinne (1964). The latter authors arrived first in the disaster area and performed a more thorough study.

2.1. Properties of fly ash

Fly ash takes the form of small spherical particles, some of them hollow. The fly ash piled up in Jupille had a well-sorted grading, with a mean diameter d_{50} of 35 μm (Table 1).

A key property of the heap material was its high porosity and, as a result, its low bulk density (1000 to 1600 kg/m^3 — Table 2). Measurements of the density of the solid phase gave values of 2150 kg/m^3 without grinding and 2600 kg/m^3 after grinding. Thus, the grinding process revealed that the amount of air entrapped in the hollow particles represented 17% of the solid phase volume (Calembert and Dantinne, 1964).

The hydraulic conductivity of the heap material was found by Calembert and Dantinne (1964) to vary between 3.5 and 6.5 × 10^{-6} m/s. These values give a permeability of about 5 × 10^{-13} m^2.

The mechanical characteristics of the low-compacted, nonsaturated fly ash were a low friction angle, ranging from 17.1 to 22.5° with a mean of 20°, and an apparent cohesion caused by capillarity forces. The apparent cohesion seemed to be very high, as suggested by the surprisingly stable steep slopes of the remaining part of the heap. Apparent cohesion is, however, dependent on the water content and it vanishes when the ash is saturated.

2.2. Heap characteristics and site topography

The Jupille heap was an almost homogeneous mass of 607,535 tons of fly ash (Fig. 1). As the heap had been raised on a relatively impervious ground composed of an upper layer of loamy clay, a water table was present at its base. A drilling in the part of the heap that was not affected by the failure revealed a water-saturated layer 5 m above the ground (total height of the heap at the drilling: 20 m) (Calembert and Dantinne, 1964).

Table 1
Fly ash grading. Percentages are on a mass basis. Measurements were performed on four probes taken from the remaining part of the heap at depths varying between 0.6 and 2.3 m. Minimum and maximum values are obtained from the deepest and shallowest probes, respectively.
Data source: Calembert and Dantinne (1964).

	d_{10}	d_{20}	d_{50}	d_{60}	d_{80}	d_{90}
Mean value (μm)	11	18	35	45	106	420
Range of values (μm)	10–12	17–20	32–40	39–54	63–181	93–1211

Table 2
Representative densities and volumetric properties of the fly ash of the heap.
Data source: CD: Calembert and Dantinne (1964); ABL: Albrecht et al. (1961).

	Ref.	Bulk density	Porosity	Degree of saturation
Upper, nonsaturated part	CD	1020 kg/m^3	0.67	45.3%
	ABL	1000 kg/m^3	0.71	56.3%
Lower, water-saturated part	CD	1510 kg/m^3	0.55	100%
	ABL	1600 kg/m^3	0.41	100%

Calembert and Dantinne (1964) give precise topographic maps (scale of 1:1700; contour intervals of 2 m) of the natural topography below the heap, the heap surface before the collapse, and the heap surface after the collapse. Based on these high resolution data, an accurate digital elevation model (DEM) could be created with a kriging method: topographic data are distributed on a 1 × 1 m Cartesian grid (Fig. 1A). Initial material heights were distributed on the same grid (Fig. 1B). A third DEM was created, including the remaining part of the heap as part of the topography instead of the initial material heights (Fig. 1C).

A topographic map covering the entire valley in which the flow occurred is not given by Calembert and Dantinne (1964). Therefore, the DEM used here is based on current topographic data of this narrow and steep-sided valley with a mild-sloped thalweg (~3°). A protection embankment built after the collapse has been removed from the model (Fig. 2).

2.3. Collapse and post-failure deposits

The failure of the heap occurred in two phases, as sketched by the arrows in Fig. 2: the initial collapse of the northern part of the heap was followed by a second and more important collapse. The first destabilized mass climbed the opposite slope of the secondary valley before sliding back to the thalweg; the second mass fell in the direction of the thalweg and followed its path. The flow ended in the main valley where it spread out and impacted several houses. The difference between the DEMs in Fig. 1B and C indicates that the overall volume of displaced material was about 206,300 m^3 (Calembert and Dantinne (1964) which gave an estimation of 100,000 to 150,000 m^3).

The contour of the deposits was mapped by Calembert and Dantinne (1964) based on aerial photography (Fig. 2). An interesting aerial photograph of the site 11 days after the accident can be found in Bishop (1973, Fig. 25a).

In the secondary valley, the flow left thin deposits, ~20 to 30 m wide, bounded by 4-m-high lateral levees (Albrecht et al., 1961). In the main valley, the deposits formed a lens, the thickness of which reached 10 m at its NW end. The lens was delimited by steep slopes, even at the places were the flow had not been stopped by houses. In the houses impacted by the flow, fly ash is reported to have filled each corner, even in the cellars (Calembert and Dantinne, 1964).

The day after the collapse, drillings were made in the deposits in the secondary valley, at a distance of about 100 m from the heap. These drillings showed that there was no mud layer at the base of the deposits. At that time, the deposits in the main valley looked dry. Their water content was found to be equal to that in the upper part of the remaining heap. With a porosity of 0.587, this means a degree of saturation of about 64%. All these observations made by Calembert and Dantinne (1964) in relation with the water content in the deposits contrast with those of Albrecht et al. (1961), who arrived two days later, at a time when the small stream flowing in the secondary valley had made its way through the deposits.