Experimental Study on the Concentration of Coarser Particles at the Frontal Segment of a Debris Flow

Takashi WADA¹, Tomohiko FURUYA¹, Kana NAKATANI¹, Takahisa MIZUYAMA² and Yoshifumi SATOFUKA³

¹ Dept. of Erosion Control Engineering, Kyoto University (Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan)
E-mail: wada0503@kais.kyoto-u.ac.jp
² National Graduate Institute for Policy Studies (7-22-1 Roppongi, Minato-ku, Tokyo 106-8677, Japan)
³ Dept. of Civil Engineering, Ritsumeikan University (1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan)

Debris flows are characterized by coarser particles being concentrated at their frontal segment during flow. To determine the underlying mechanism of this effect, we carried out flume experiments with sediment mixtures, in which the flume length, bed roughness, and flume inclination were varied. In our experiments, we investigated the phenomenon of frontal segment concentration of coarser particles using two lengths of flume, which were considered movable, and two fixed beds at different levels of bed roughness. The flume inclination was varied systematically in the 3–18° range. The experiments were conducted under conditions that have not been examined sufficiently in previous flume experiments. We obtained several useful findings regarding the relationships between the various experimental conditions and the mechanism underlying the concentration phenomenon and provide a qualitative analysis of the mechanism based on our findings. The analysis indicates that even when coarser particles do not rise to the upper layer in the interior of a debris flow, they tend to concentrate at the frontal segment as the finer particles fall and migrate backward from the frontal segment.

Key words: debris flow, concentration of coarser particles, falling of finer particles, frontal segment of debris flow, flume experiment

1. INTRODUCTION

Debris flows are characterized by coarser particles being concentrated at their frontal segment while flowing downwards; this has been reported in many studies [Sharp et al., 1953; Okuda et al., 1977; Suwa et al., 1984; Suwa et al., 1986; Teramoto et al., 2002]. Additionally, this phenomenon has been observed in previous flume experiments on debris flows consisting of sediment mixtures [e.g., Hashimoto and Tsubaki, 1983; Miyamoto, 1986; Suwa, 1988; Takahashi et al., 1990; Takahama, 1991; Satofuka et al., 2007; Iverson et al., 2010; Iwata et al., 2013]. The devastation and loss of life caused by debris flows in flooding areas, such as alluvial fans, can be extensive because the destructive force of the flow is augmented by this concentration phenomenon.

Several theories have been proposed to explain the mechanism underlying this characteristic of debris flows [Bagnold, 1968; Middleton, 1970; Takahashi, 1980; Hashimoto and Tsubaki, 1983; Miyamoto, 1986; Suwa, 1988; Maeda et al., 2011]. Based on an observation regarding the “inverse grading” found in debris flow deposits [e.g., Suwa et al., 1982], in which the particle sizes increased towards the upper layer of deposition, these theories considered this effect to be a result of gravels of different particle sizes switching inside the flow along its depth as it flows down. This results in that the coarser particles moving upwards and the finer particles moving downwards; the coarser particles rising to the upper layer are transported to the front because of an increased flow velocity in the upper layer versus that in the lower layer.

However, these theories propose different mechanisms to explain inverse grading in the interior of a debris flow. Bagnold [1968] developed a theory in which the dispersive stress increased with the square of particle diameter for a given shear
rate; the coarser particles in a debris flow under shear tended to drift towards the region of least shear; that is, towards the upper, free surface of the flow. Middleton [1970] assumed that the finer particles fell into the interstices between the coarser particles, and the coarser particles were pushed upwards by the finer particles (dynamic sieving). Hashimoto and Tsubaki [1983] explained the mechanism with a theory in which, for the interior of a debris flow that has a high concentration of gravel, momentum is gathered not only because of transmission by collision, but also by contact between particles, because when particles flow down, they contact each other for a short while as well as colliding. Miyamoto [1986] explained the mechanism on the basis of particle technology, positing the notion that the finer particles fall into the interstices between coarser particles (percolation), because this characteristic occurs not only in multiphase flows consisting of fluid and solid particles, but also in granular materials consisting only of solid particles.

Additionally, numerical computations using distinct element methods have been reported. For example, Maeda et al. [2011], based on the results of experiments with alumina balls and a numerical computation of distinct element methods for dry granular flows, explained that this characteristic of debris flows was a result of the coarser particles being pushed up, towards the surface, by stress chains (transmission of contact forces) formed in the interior of a debris flow. However, Suwa [1988] proposed a theory in which this characteristic was not a result of inverse grading in the interior of a debris flow, but of the velocities of the coarser particles in the direction of the flow being higher than the velocity of the overall flow. Thus, these theories differ significantly in terms of “inverse grading” or the transport of coarser particles within the interior of the flow. In addition, none of the theories have been sufficiently confirmed. Thus, a conclusion cannot yet be drawn regarding the mechanism underlying this characteristic of debris flows.

In mountainous streams, in which debris flows are likely to occur, the gradient, travel distance, and bed roughness may vary. Furthermore, the particle size distribution and volume of debris flows also vary significantly. It is thus necessary to investigate how these factors affect the concentration of coarser particles at the frontal segment of the flow. In previous flume experiments, the conditions were determined by varying several factors: flume length, bed roughness, flume inclination, and particle size distribution of the materials. However, the experimental conditions were not consistent among these experiments (see Table 1), making it difficult to compare results.

Thus, to clarify the mechanism underlying the concentration of coarser particles at the frontal segment of a debris flow, the purpose of this study was to determine the relationships between this phenomenon and several different factors. We carried out flume experiments with sediment mixtures, where the flume length, bed roughness, and flume inclination were varied. Assuming that the concentration of coarser particles at the frontal segment of the flow develops during its flowage in mountainous streams, we included the factors that affected the flow directly as the target factors for our experiments: flume length, bed roughness, and flume inclination.

2. EXPERIMENT

2.1 Experimental conditions

We set the experimental conditions by considering combinations of the following parameters: flume length, bed roughness, and flume inclination. To compare the results of our experiments with those of previous flume experiments (Table 1), we set the values of these factors according to the conditions used in these previous experiments. The reasoning behind setting the values of these factors in this manner is as follows.

The flume lengths in previous experiments were within the order of 1 m, except for the experiments done by Miyamoto [1986] and Iverson et al. [2011]. Furthermore, only one type of flume length was adopted, except for the experiments by Takahashi et al. [1990], in which four different flume lengths were used. Thus, we conducted experiments with two flume lengths of the order of 1 m, and compared the results of these experiments to investigate the effect of travel distances on the concentration of coarser particles at the frontal segment of a debris flow.

Concerning the bed conditions, in previous experiments either a movable bed or a fixed bed was considered, except for the experiments done by Iverson et al. [2010], in which two fixed beds were considered: a smooth concrete surface and a tile-covered surface with regularly spaced, rounded conical bumps. Thus, we conducted experiments with a movable bed and two fixed beds different levels of roughness, and compared the results of these experiments to investigate the effects of bed conditions on this characteristic of debris flows.
Many of the flume inclinations in the previous experiments were larger than 15°. This was because the concentration of coarser particles at the frontal segment of a debris flow often occurred on a relatively large gradient. However, Ashida et al. [1978] and Hashimoto and Tsubaki [1983] both reported that coarser particles concentrated at the frontal segment of the flow even on a small gradient. Thus, we conducted experiments varying flume inclinations systematically over a wide range.

### Table 1 Characteristics of flume experiments with sediment mixtures in previous studies.

| Previous experiments | Occurrence of a debris flow | Measurement | Flume length (cm) and bed condition | Flume inclination (°) | Materials (Diameter : Initial mixed ratio) | Flow discharge by a unit width (cm²/s) | $h_{max}/d_{max}$ |
|----------------------|-----------------------------|-------------|-------------------------------------|----------------------|-------------------------------------------|----------------------------------------|------------------|
| **Hashimoto and Tsubaki, 1983** | Erosion of movable bed | • Volume fractions of particles at downstream end | 700 Movable bed | 6–22 | 14.7 mm : 80% | 200 | 2.3–3.4 |
| **Miyamoto, 1986** | Erosion of movable bed | • Volume fractions of particles at downstream end | 1,200 Movable bed | 15 17 20 22 | Mixtures 2 particles with diameters in the range of 2–15 mm | 200 | 2.2–2.5 |
| **Suwa, 1988** | Erosion of movable bed | • Number, velocity and moving trace of coarser particle | 490 Movable bed | 6.2 9 | 24 mm : 33% | 1,000 (Supplying instantly) | 2.1 |
| **Takahashi et al., 1990** | Erosion of movable bed | • Time series of volume fractions of particles at downstream end | 100 200 300 400 Movable bed | 15 18 21 | 4.38 mm : 20% | 200 | 7.7–8.6 |
| **Takahama, 1991** | Constant supplying of water and sediment | • Time series of volume fractions of particles at downstream end | 150 240 360 Fixed bed | 16 18 20 25 | Mixture: two particles with diameters in the range of 0.769–3.79 mm | 200 | 5.1–5.6 |
| **Satofuka et al., 2007** | Pull-up of the material stopper | • Time series of volume fractions of particles at downstream end | 300 Fixed bed | 17 | 14.1 mm : 25% | 91 | 1.6 |
| **Iversion et al., 2011** | Pull-up of the material stopper | • Distribution of depth and volume fractions of deposition on flood plane at downstream end | 9,500 Fixed bed (two types of roughness) | 31 | 2–32 mm : 66% | 50,000 (Saturated material) | 62.5 |
| **Iwata et al., 2013** | Erosion of movable bed | • Time series of volume fractions of particles at downstream end | 800 Movable bed (300 cm) and Fixed bed (500 cm) | 15 | 2.9 mm : 0% | 200 | 6.9 |
from gentle to steep, and compared the results to investigate the effect of gradients.

The materials used in the previous experiments varied widely, with different particle size distributions. In these previous experiments, the ratio of the maximum depth of the flow $h_{\text{max}}$ to the maximum diameter of the particles in the flow $d_{\text{max}}$ was typically $1 < h_{\text{max}} / d_{\text{max}} < 10$. Here, $h_{\text{max}}$ was the experimental result or the value estimated using Manning’s formula with a Manning coefficient of roughness of $n_m = 0.109$ [Okuda et al., 1977]. Thus, we set the maximum diameters of the materials and the flow discharge supplied from the upstream end of the flumes in our experiments to have $1 < h_{\text{max}} / d_{\text{max}} < 10$. Because a debris flow is composed of various particle sizes, the materials used in our experiments were mixtures of particles of several different diameters.

The experimental conditions in our experiments are listed in Table 2. Case 1 describes the base conditions used. In Cases 2–4, the values of only a few factors were different from those in Case 1 and all other factors were the same. In Case 2, the flume length was longer than in Case 1. In Case 3, the flume length was equal to that in Case 2, and in the extended segment, compared with Case 1, a fixed bed with coarse particles formed from an equivalent-mass mixture of six different-sized particles within the size range of 2.83–12.07 mm was prepared. In Case 4, the flume length was also equal to that in Case 2, and a fixed bed with fine particles with a diameter of 2.83 mm was prepared in the extended segment. In all cases except Case 2, the flume inclination was varied in the 3–18° range in 3° increments. In Case 2, 12°, 15°, and 18° were used for the flume inclination.

### Table 2 Experimental conditions examined in the experiments.

| Case | Material used for experiments | Bed condition of flumes | Flume length (cm) | Flume inclination (°) |
|------|-------------------------------|------------------------|-------------------|----------------------|
| Case1 | Equivalent-mass mixture of six different sizes of particle with diameters in the range of 2.83–12.07 mm | Movable bed<sup>1</sup> | 175 | 3–18 (in 3° step) |
| Case2 | and movable bed<sup>1</sup> on fixed bed | Movable bed<sup>1</sup> and movable bed<sup>1</sup> on fixed bed | 475 | 12–18 (in 3° step) |
| Case3 | Movable bed<sup>1</sup> and fixed bed with coarse particles<sup>2</sup> | Movable bed<sup>1</sup> and fixed bed with coarse particles<sup>2</sup> | 475 | Movable bed 175 cm and fixed bed 300 cm |
| Case4 | Movable bed<sup>1</sup> and fixed bed with fine particles<sup>3</sup> | Movable bed<sup>1</sup> and fixed bed with fine particles<sup>3</sup> | 175 | 3–18 (in 3° step) |

1) Movable bed consists of materials used for each case.
2) Coarse particles were an equivalent-mass mixture of six different sizes of particle with diameters in the range of 2.83–12.07 mm (equivalent sand roughness was 5.94 mm).
3) Fine particles were the particle with a diameter of 2.83 mm (equivalent sand roughness was 3.53 mm).

The equipment and experimental procedure are shown in Fig. 1. We carried out experiments with a movable sampler that consisted of four boxes, a high-speed video camera (Exilim Pro EX-F1, Casio, Tokyo, Japan), and two tilted straight flumes of different lengths. The materials used in our experiments were equivalent-mass mixtures of six different-sized particles within the size range of 2.83–12.07 mm, obtained by screening from commercially available natural river gravels (Fig. 2). The mean particle diameter was 5.99 mm; the parameter for the particle size distribution $(d_{50}/d_{10})^{1/2}$ was 1.95, the density of the particles was 2.50 g/cm³, and the concentration in the static sediment bed was $C_0 = 0.62$.

The experimental procedure was as follows. After we placed the materials in the movable bed section of the flume, water was supplied at a flow rate of 100 cm²/s, a unit width from the upstream end. While flowing in the movable bed, water eroded the bed and generated a debris flow. When the debris flow arrived at the downstream end, we began to move the sampler at a constant speed in the
direction transverse to the flow, and the debris flow was divided and flowed into the four boxes, allowing us to obtain four samples successively from the front of the flow at constant time intervals in the range 1–3 s. In this study, the “frontal segment” was defined as the range in which the surge of the debris flow occurred. As shown in Fig. 3, this range was almost within 3 s because the debris flows arrived at the observation point in all cases. Thus, the sample of the “frontal segment” of the debris flow was defined as the first of the four samples. We also measured the time interval of the flow into each box. From these samples and the time intervals, we measured the time series of the total flow discharge, sediment discharge, sediment concentration of all of the particles, sediment concentration of each size of particle, and the particle size distribution.

In Cases 2–4, at the point 325 cm from the upstream end of the flumes, we filmed the movement of the particles in the interior of the debris flows using a high-speed video camera. We measured the flow depth, flow velocity, and migration velocities of particles in the flow direction, and the direction perpendicular to the flow direction, by motion analysis of video records. The particles analyzed were those that could be reliably traced in the view field of the videos for 3 s since the flows arrived at the specified point.

The above processes and measurements were repeated three times for each case, and for each flume inclination.

3. RESULTS AND DISCUSSION

3.1 Temporal changes in quantities describing the particle in the frontal segment of a debris flow

Figures. 4–7 show the temporal changes in the mean diameter and sediment concentrations of all particles, as well as those of the particles of maximum (diameter = 12.07 mm) and minimum (diameter = 2.83 mm) size, obtained at the downstream end of the flumes in Cases 1–4 with a flume inclination of 15°. In all cases, the mean diameters and sediment concentrations of the particles of maximum size increased towards the front of the debris flows, whereas the sediment concentration of the particles of minimum size decreased. This trend was observed for all flume inclinations. Thus, we found that the coarser particles were concentrated at the frontal segment of a debris flow while flowing downwards, regardless of the flume length, bed condition, or flume inclination. These results were in good agreement with those reported by Hashimoto and Tsubaki [1983], where the coarser particles were found to be concentrated near the front of the flow even with a relatively small inclination (~6°). In cases where the bed roughness was relatively large (e.g., Case 3), compared with other cases, the peak sediment concentration of all particles occurred after the frontal segment of the flows, as shown in Fig. 6. This was because the migration velocities of the particles in the flow direction were less than that of the water due to the collisions and friction of the particles in the flow and the fixed particles on the bed. In this respect, the conditions at the frontal segment of the flows in Case 3 differed from those of the other cases. Nevertheless, similar to the other cases, the mean diameter and sediment concentration of the particles of maximum size increased in the samples closer to the front of the flow. Thus, the concentration of coarser particles at the frontal segment of a debris flow was hardly affected by the conditions (i.e., the sediment concentration of all particles) at the front of the flow.

3.2 Volume fractions of particles of each size in the frontal segment of a debris flow

Figures. 8–11 show the volume fraction of particles of each size in the frontal segment of debris flows at the downstream end of the flumes in Cases 1–4. These figures show that as the particle size became coarser, the volume fraction of the particles in the frontal segment of a debris flow increased regardless of the flume length, bed roughness, or flume inclination.
If a particle size was coarser than the mean size of the particles in the materials in the frontal segment of a debris flow, the volume fraction of that particle increased to a value more than its initial volume fraction in the frontal segment. However, if a particle size was finer than the mean size of the particles in the materials in the frontal segment, the volume fraction of that particle decreased to a value less than its initial volume fraction in the frontal segment. Concerning the variation in flume length in Cases 1 and 2, the volume fraction of coarser particles in the frontal segment increased as the flume length increased. These trends were also reported by Takahashi et al. [1990]. Concerning the variation in bed roughness in Cases 3 and 4, the volume fractions of coarser particles in the frontal segment increased as the bed roughness increased. This trend was also reported by Iverson et al. [2010]. The change in the volume fractions of coarser particles in the frontal segment with larger flume inclinations was different from that with longer flume lengths and greater bed roughness. In all cases, the volume fractions of coarser particles in the frontal segment did not increase monotonously with flume inclination. In summary, similar to the results of previous studies, coarser particles tended to concentrate in more significant quantities in the frontal segment of a debris flow with longer flume lengths and greater bed roughness; however, the concentration of coarser particles at the frontal segment did not vary monotonously with the flume inclination.

3.3 Migration velocities of the particles at the frontal segment of a debris flow

Figures 12–14 show the migration velocities of the particles of maximum and minimum size in the flow direction and the direction perpendicular to the flow direction at a point 325 cm from the upstream end of the flumes, for Cases 2–4. These figures also show the mean migration velocities of the particles.
First, we describe the characteristics of the migration velocities of the particles of maximum and minimum size in the flow direction. In Cases 2 and 4, there were marginally significant differences (0.05 < p < 0.10) between the migration velocities of the particles of maximum and minimum size in the flow direction, at a given depth of the frontal segment. The migration velocities of the particles of minimum size in the flow direction were larger than those of the particles of maximum size at a given depth of the frontal segment. This differs from the results of previous experiments [e.g., Hashimoto and Tsubaki 1983; Takahama, 1991; Iwata et al., 2013], and the theory proposed by Suwa [1988], which indicated that the migration velocity of a particle in the flow direction was larger with coarser particle sizes in the interior of the flow. However, in Case 3, there were significant differences (p < 0.05) between the migration velocities of the particles of maximum and minimum size in the flow direction at the depth near the bed at the frontal segment, and the migration velocities of the particles of minimum size in the flow direction were smaller than those of maximum size at the depth near the bed at the frontal segment. This was caused by the flow velocity decreasing near the bed and the friction induced by the frequent collisions between flowing particles and fixed particles on the bed due to high bed roughness. In summary, the migration velocities of the particles of minimum size in the flow direction at the frontal segment were slightly larger than those of the particles of maximum size; however, when the bed roughness was increased, the migration velocities of the particles of minimum size, at the depth near the bed at the frontal segment, were less than those of the particles of maximum size.

Next, we describe the characteristics of the migration velocities of the particles of maximum and minimum size in the direction perpendicular to the flow direction. There was no significant difference (p > 0.10) between the migration velocities of the particles of maximum and minimum size in the direction perpendicular to the flow direction at the frontal segment of a debris flow in Cases 3 and 4, in which the flow depth was relatively small. However, in Case 2, where the flow depth was relatively large, there were marginally significant differences between these velocities in the frontal segment, and the downward velocities of the particles of minimum size were higher than those of the particles of maximum size at the frontal segment. In addition, the average migration velocities of the particles of maximum and minimum size in the direction perpendicular to the
The migration of the finer particles towards the lower layer was more marked. Cases 2 to 4, in which the flow direction was almost negative (falling) in the frontal segment, suggested that the materials were almost negative (falling) in the frontal segment proposed by Middleton [1970], Hashimoto and Tsubaki [1983], and Miyamoto [1985] (the mechanism predicted by Hashimoto and Tsubaki, and by Miyamoto, is for cases where coarser particles comprised the majority of the materials). Specifically, it was seen that the finer particles fell to the lower layer through the interstices between the particles in the interior of the flow, and the coarser particles hardly moved downwards, because their sizes were larger than the interstices. In the proposed theory, the sizes of the interstices depend on the sizes of the neighboring particles in the interior of the flow. Thus, the size of the interstices between the particles increases with a greater volume fraction of coarser particles at the frontal segment, and it is possible for coarser particles in the interior of the flow to fall to the lower layer through the interstices between the particles in the interior of the flow.

These results regarding the migration velocities of the particles at the frontal segment of a debris flow provide insight into the mechanisms underlying the concentration of coarser particles at the frontal segment proposed by Middleton [1970],
particles to fall to the lower layer through the interstices. This is supported by the fact that, as the flume length increased, the volume fraction of coarser particles at the frontal segment of a debris flow increased and the volume fraction of finer particles at the frontal segment decreased (see Figs. 8 and 9). However, these results differed from the mechanisms proposed by Middleton [1970], Hashimoto and Tsubaki [1983], and Miyamoto [1985], in that particles of any size exhibited a generally downward movement at the frontal segment of a debris flow. These results regarding the concentration of coarser particles at the frontal segment of a debris flow can be explained mainly by the falling of the finer particles towards the lower layer, through the interstices between the particles in the frontal segment. This was supported by the fact that, in Case 4, the migration velocity of the particles of minimum size, towards the lower layer at the frontal segment of a debris flow, was relatively low (see Figs. 12–14), and the volume fractions of coarser particles at the frontal segment were also the lowest, comparison with the results from Cases 2–4 (see Figs. 9–11). These results also differ from the mechanisms proposed by Middleton [1970], Hashimoto and Tsubaki [1983], and Miyamoto [1985], in that the migration velocities of finer particles at the frontal segment were larger than those of coarser particles in the flow direction. However the difference between the migration velocities of coarser and finer particles in the flow direction at the frontal segment hardly influenced the concentration of coarser particles at the frontal segment, because the volume fractions of finer particles at the frontal segment were smaller than those of coarser particles in all cases (see Figs. 8–11).

3.4 Mechanism underlying the concentration of coarser particles at the frontal segment of a debris flow based on the results of our experiments

Considering the results and discussion of our experiments in sections 3.1–3.3, we suggest that the concentration of coarser particles at the frontal segment of a debris flow was due to the following factors (see Fig. 15):

1. Finer particles fall to the lower layer through the interstices between particles in the frontal segment of a debris flow, whereas coarser particles cannot fall easily because their sizes are larger than the sizes of the interstices.
2. The finer particles that fall to the lower layer have slower migration velocities in the flow direction than the coarser particles, and move backward from the frontal segment in the flow.
3. Coarser particles remain at the frontal segment of the flow, and finer particles are removed.
4. The sizes of the interstices between the particles at the frontal segment increase with the greater volume fraction of coarser particles at the frontal segment. Consequently, it is possible for coarser particles to fall to the lower layer through the interstices.

By repeating steps 1) to 4), coarser particles become concentrated at the frontal segment of the flow while flowing down. Although finer particles are supplied in greater volumes to the frontal segment than coarser particles, due to the higher migration velocities of the finer particles, the volume fraction of finer particles at the frontal segment decreases as the finer particles fall and migrate backwards from the frontal segment. This mechanism shows that the concentration of coarser particles at the frontal segment of a debris flow can be explained by the “falling and backward migration from the frontal segment” of the finer particles, even when migration towards the upper layer of coarser particles does not
occur in the interior of the flow.

4. CONCLUSION

In our study, we carried out flume experiments with sediment mixtures, where the flume length, bed roughness, and flume inclination were varied, to determine the relationships between these factors and the concentration of coarser particles at the frontal segment of a debris flow and clarify the mechanism involved. We obtained several useful findings regarding these relationships and provided a qualitative analysis of the mechanism explaining our experimental findings. The analysis indicates that even when coarser particles do not rise to the upper layer in the interior of a debris flow, they tend to concentrate at the frontal segment of a debris flow because the finer particles “fall and migrate backward from the frontal segment.” However, this does not explain the movement of coarser or finer particles in the frontal segment of a debris flow during the development of the flow. Further studies into these aspects are still necessary. Additionally, this analysis is qualitative and based on the results of only a few experiments conducted under a limited range of conditions. Therefore, it is important to confirm the validity of this analysis quantitatively, via further experiments conducted under a broader range of experimental conditions.

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