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# An experimental study of the dynamics of subaqueous sediment gravity flows

## Etude expérimentale de la dynamique des écoulements gravitaires subaquatiques de sédiments

J. Miyamoto
*Kiso-Jiban Consultants Co., Ltd., Japan*

S. Sassa
*Port and Airport Research Institute, Japan*

R. Tokuyama
*P.S. Mitsubishi Construction Co., Ltd., Japan*

H. Sekiguchi
*Disaster Prevention Research Institute, Kyoto University, Japan*

ABSTRACT
This paper examines the flow potential of subaqueous sediment gravity flows through a set of flume tests. The emphasis of the experiments was placed on clarifying the internal structure of fluidized sediment gravity flows in terms of a PIV technique. It was found that in the course of fluidized gravity flow, solidification initially occurred at the base of the flowing fluidized sediment and then propagated upwards to the flow surface, terminating the flowage. In fact, the progressive solidification in the fluidized sediment flow enabled a grain-supported framework to be reestablished, with no or little settling of particles. This performance was contrasting with the performance of suspension-dominant flows in which settling of particles was an essential facet leading to deposition.

RÉSUMÉ
Cette étude examine le potentiel de fluidité des écoulements gravitaires des sédiments à travers une série d'expériences dans une cuve. Elle a pour but de fournir des indices dans la compréhension de la physique des mouvements subaquatiques en masse de sédiments. Elle s'est concentrée particulièrement sur l'observation de la structure interne des écoulements gravitaires de sédiments fluidifiés ainsi que des écoulements gravitaires de sédiments en suspension. Les résultats des expériences ont montré que lors du processus des écoulements gravitaires des sédiments fluidifiés, une solidification du sable liquéfié de la partie profonde du flux se produisait. Cette zone solidifiée se propageait ensuite jusqu'à la surface de l'écoulement. Ce résultat contraste avec les écoulements gravitaires de sédiments en suspension où la déposition des particules de sable prédomine.

## 1 INTRODUCTION

Sediment gravity flows under water have become an increasingly important subject for research in relation to geomorphodynamics of sediment routing systems that connect river basins, estuaries and coastal oceans. Also, submarine landslides and flow slides have received considerable practical attention in view of their destructive power and associated consequences in nearshore and offshore facilities (Hampton et al. 1993; Bea et al.1983). Fluid-sediment interactions are a key process that features any of subaqueous sediment gravity flows. Thus integration of fluid-dynamics and soil-mechanics approaches will be indispensable in advancing the physics of subaqueous sediment gravity flows. It is of interest in this regard to note that the importance of pore water pressure in the dynamics of debris flows was pointed out by Iverson (1997).

The present study attempts to explore physical aspects of liquefied or fluidized sediment gravity flows, in close association with a theoretical work by Sassa et al. (2003). They emphasized the two-phased nature of liquefied sediment and presented an analysis procedure in which Navier-Stokes equations (for liquefied soil) were combined with a consolidation equation (for initially liquefied but currently solidifying soil), along with the idea of progressive solidification. Progressive solidification is a sort of phase-change process (Miyamoto et al., 2004) and allows transitory fluid-like particulate sediment to reestablish a grain-supported framework during continued disturbances. As such, it may exert a profound influence on the process of flowage of particulate sediments and warrant scrutiny through physical testing.

The subsequent sections will discuss results of flume tests on subaqueous sediment gravity flows that follow abrupt collapse. The emphasis of the discussion will be placed on examining the effect of initial volumetric concentrations on flowage characteristics. Furthermore, the evolution of internal flow structure will be carefully examined using a particle image velocimetry (PIV) technique, with the aim of clarifying the nature of progressive solidification during flowage.

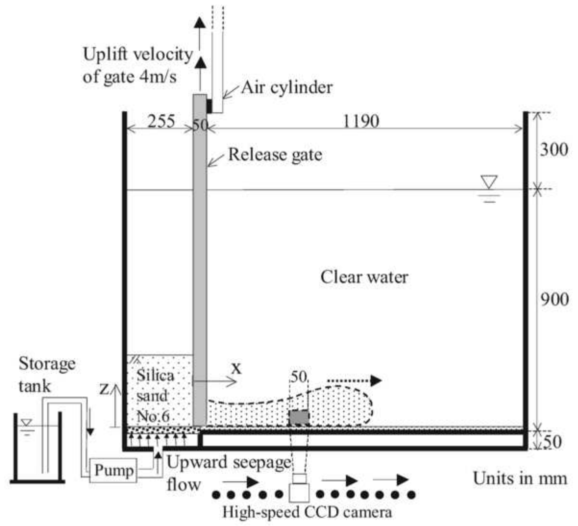

Figure 1. Setup for experiments on sediment gravity flows

## 2 CHARACTERISTICS OF SEDIMENT GRAVITY FLOWS

The flume used is shown in Fig. 1. A deposit of sand was formed in a 255-mm wide reservoir while a release gate was completely closed. The deposit of sand was subjected to upward seepage flow under a given discharge velocity, yielding an initially liquefied, fluidized or suspended state of sediment. Then the release gate was swiftly opened, allowing the sediment to flow out over a horizontal floor in the channel. The movement of the sediment was captured using a high-speed CCD camera (recording rate: 250 frames/s; shutter speed: 1/1000 s and resolution: 640×240). A PIV technique was applied to a range of

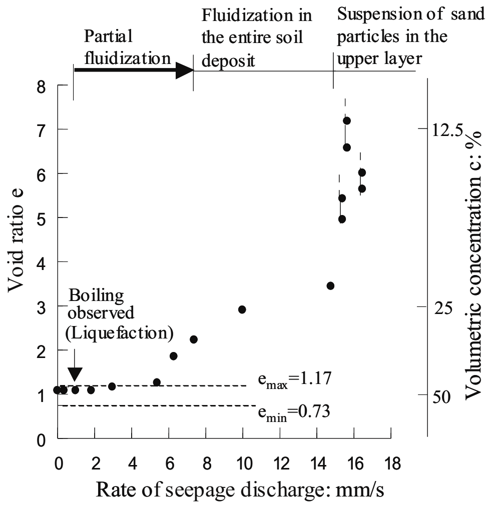


Figure 2. Void ratios of sediment plotted against vertical seepage velocities imposed, showing soil-state transformation

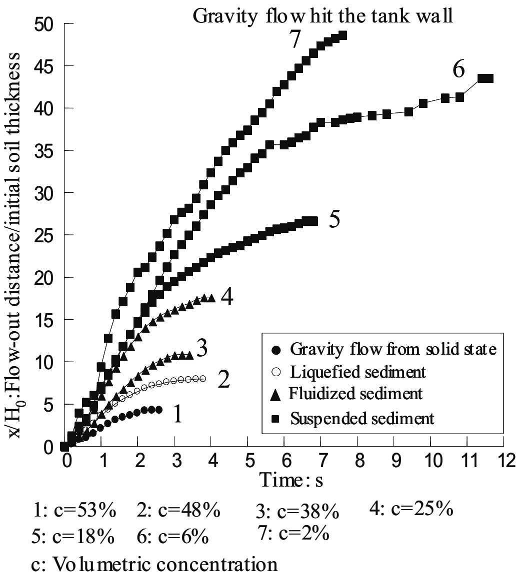


Figure 3. Measured time histories of location of gravity flow head

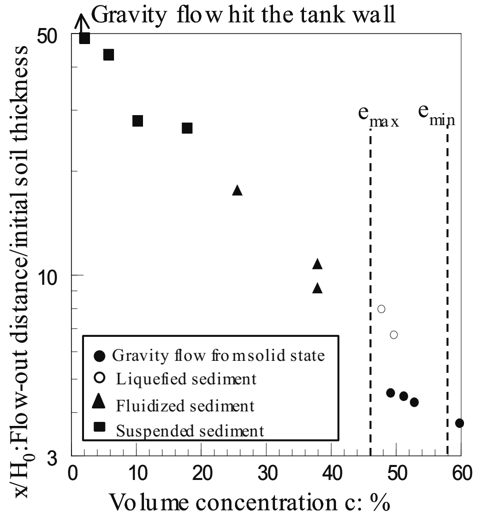


Figure 4. Non-dimensional flow-out distances plotted against volumetric concentrations of sediment prior to flowage

imagery obtained with the high-speed CCD camera, providing a useful dataset regarding the evolution of the velocity field in the sediment gravity flow. We used a PIV-software named KUpiv_v1 (Kimura et al. 2001) for the image processing.

The sand used in the flume tests was silica sand No. 6 (Gs=2.65m, $e_{max}$=1.17, $e_{min}$=0.73 and $D_{50}$=0.32mm). A sand layer 5mm thick was placed in each test on the floor of the channel in order to achieve realistic boundary conditions for the sediment gravity flow.

The state of the sand deposit in the reservoir was controlled by varying the upward seepage velocity imposed (Fig. 2). It underwent boiling (or liquefaction) at a seepage velocity of about 1 mm/s. The soil surface gradually heaved with increasing seepage velocity, showing slight increase in void ratio (or slight decrease in volumetric concentration, c). Fluidization of the entire sediment occurred when the seepage velocity ranged from 5 mm/s up to 15 mm/s or so. Note that the volumetric concentrations of the fully fluidized sediments were high, namely in the range of c=48% down to 20% or so. When the seepage velocity was increased further beyond 15 mm/s, the upper layer of the sediment became suspended while its top surface remained in the reservoir. A water-circulating system (not shown in Fig. 1) was installed in the flume when forming low-concentrated sediment suspensions (c=2%-6%).

It is evident in Fig. 3 that the flow potential of the sediment gravity flow significantly changed according to the initial states of the sediment: namely solid (sub-liquefied); liquefied; fluidized; or suspended. Here the measured time histories of location of the gravity flow head are shown for the seven different volumetric concentrations indicated. The normalized flow-out distances x/Ho are plotted in Fig. 4 against the volumetric concentrations, c. It is evident that when liquefied, the flow potential of the sediment increased to a significant extent; this may be due to the complete loss of the effective stress upon liquefaction. In the regime of fluidized sediments, no effective stress can be conceivable. Thus the increase in flow potential in this regime may be induced with decreasing volumetric concentration.

## 3 INTERNAL STRUCTURES OF SEDIMENT GRAVITY FLOWS

This section will compare the internal structure of a fluidized sediment gravity flow (c=38%) with that of a suspension-dominant gravity flow (c=2%). For purposes of description, the latter will be referred to first.

### 3.1 *Suspension-dominant gravity flow*

Snapshots of a suspension-dominant gravity flow (c=2%) at four different times are shown in Fig. 5(a). Here, $T_a$ is instant of time when the flow head arrived at the station of observation (x=890mm). These pictures were taken using the high-speed CCD camera and were processed, in terms of the PIV technique, to give the velocity fields shown in Fig. 5(b). It is noteworthy that the initially suspended sand particles in the lower part of the domain of observation underwent gradual settling during horizontal flowage, thereby yielding moderate deposition. The settling behaviour during flowage may also be confirmed in Fig. 5(c) where the distributions of horizontal and vertical velocities with elevation are shown for the four different times indicated.

### 3.2 *Progressive solidification in fluidized sediment gravity flow*

Snapshots of a fluidized sediment gravity flow taken with the high-speed CCD camera are shown in Fig. 6(a) for the four different times indicated. The sediment was initially in a fully fluidized state, with a volumetric concentration c as high as 38%. The flow surface (FS) became apparent 0.5 seconds after the

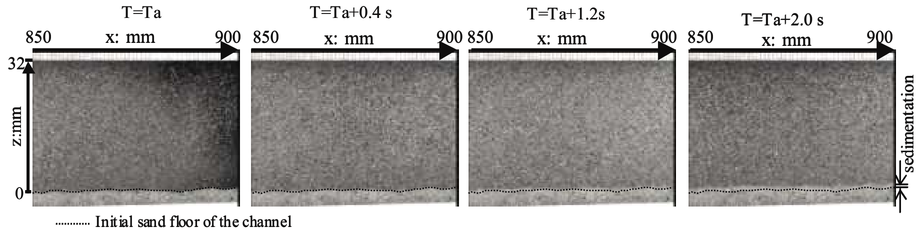

Figure 5 (a). Snapshots of suspension-dominant gravity flow at four different instants of time from a fixed station

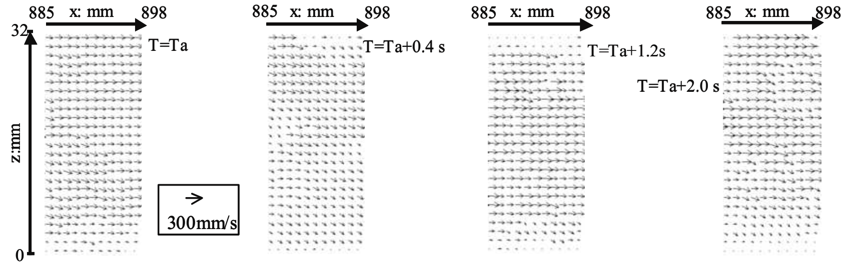

Figure 5 (b). Velocity fields of suspension-dominant gravity flow at four different instants of time, obtained using PIV technique

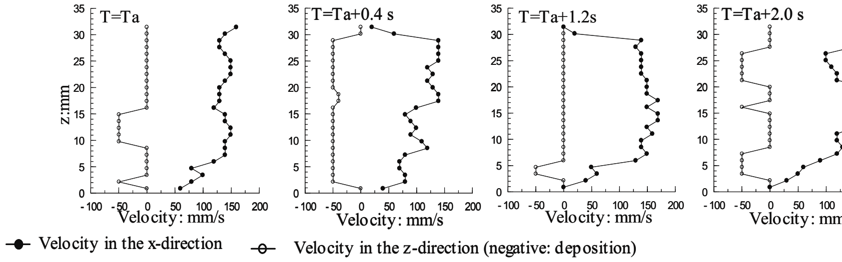

Figure 5 (c). Profiles of flow velocities with elevation, at x=890mm, at four different instants of time

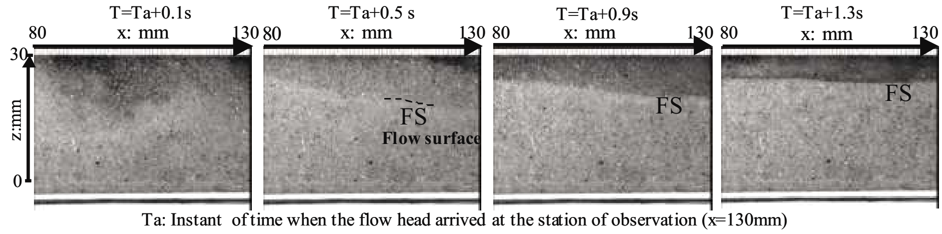

Figure 6 (a). Snapshots of fluidized sediment gravity flow at four different instants of time from a fixed station

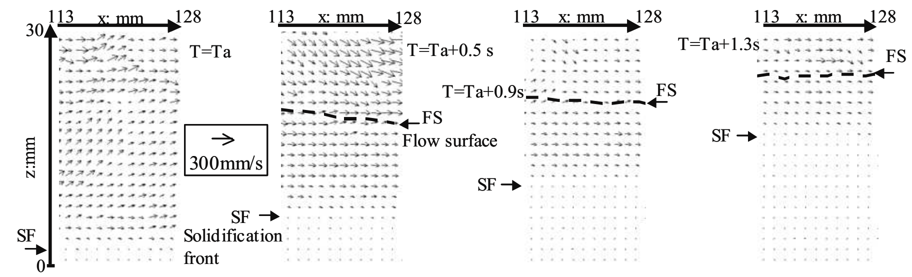

Figure 6 (b). Velocity fields of fluidized sediment gravity flow obtained by PIV technique, showing developments of solidification

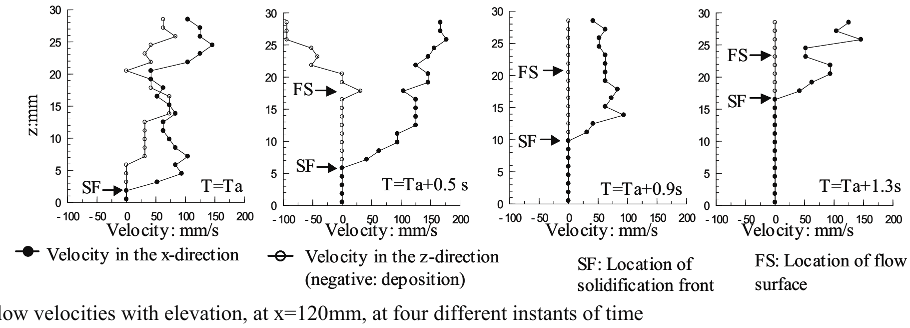

Figure 6 (c). Profiles of flow velocities with elevation, at x=120mm, at four different instants of time

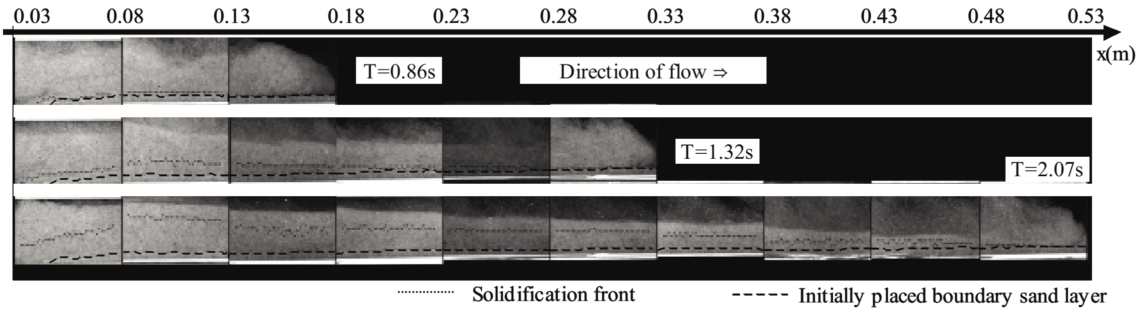


Figure 7. A series of pictures showing the flow-out of initially fluidized sediment following abrupt collapse, together with solidification front identified by PIV technique

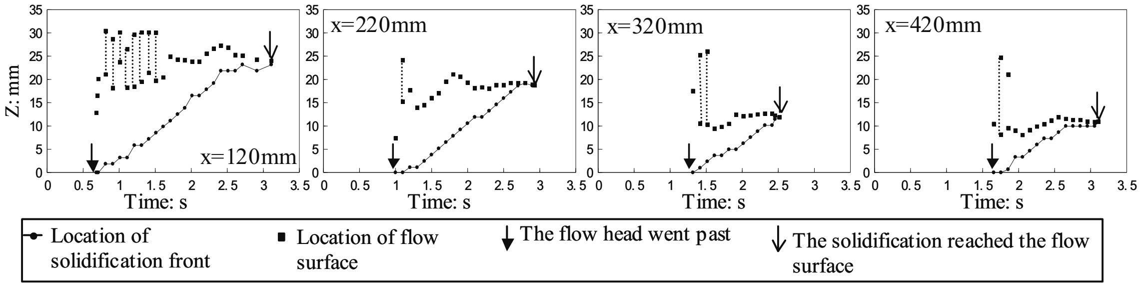


Figure 8. Evolutions of flow surface and solidification front at four different stations, showing instants of time of flow termination

gravity flow head passed the station x=130mm under consideration, and thereafter the flow surface became clearer. On such imagery, however, one cannot identify the formation of any solidification zone. Interestingly, the velocity fields obtained using the PIV technique revealed the developments of solidification zones, as shown in Fig. 6(b). Note that the region with zero velocities spreads upwards as time lapses, indicating the occurrence of progressive solidification during flowage. The upper boundary of the solidification zone is called the solidification front (SF), which actually is a moving interface between the zone of completely fluidized sediment and the zone with a grain-supported framework being reestablished. The velocity profiles obtained for the fluidized sediment gravity flow are shown in Fig. 6(c). Note the flow stratification after the flow surface (FS) was formed. Namely, the fluidized sediment gravity flow consisted of three regions: $0<z<SF$; $SF<z<FS$ and $FS<z$. The region between the base and the solidification front ($0< z<SF$) was the solidification zone in which the sand particles had zero velocities. In the region $SF<z<FS$, the sand particles flew only in the horizontal (x) direction, with essentially no vertical movements. In contrast, the region above the flow surface ($FS<z$), the sand particles underwent the horizontal and vertical movements in a manner similar to the afore-mentioned behavior of the suspension-dominant gravity flow.

Let us now look at an overall picture of flowage of the fluidized sediment gravity flow with c=38% (Fig. 7). This representation was made possible by performing the ten identical flume tests and by assembling pictures recorded from the ten differing stations with the single CCD-camera. A close look at Fig. 7 permits one to grasp the movement of the head of the gravity flow. Also, it facilitates a good understanding as to how the initially fluid-like body of sediment gravity flow underwent solidification progressively in the course of flowage.

Indeed, one can readily confirm in Fig. 8 that as soon as the head of the gravity flow went past a given station, solidification started developing at that station from the base up, eventually reaching the flow surface. It is interesting in this regard to note that the velocities of advance of the solidification front at the four stations were approximately the same in value (about 12mm/s). It is also noteworthy that the solidification front reached the flow surface essentially the same instant of time at the four stations under discussion. This suggests the occurrence of abrupt stoppage or "freezing" of the fluidized sediment gravity flow, inspiring a future theoretical analysis.

## 4 CONCLUSIONS

The flow-out potential of subaqueous sediment gravity flows following abrupt collapse has been discussed through a comprehensive set of flume tests. The principal conclusions may be summarized as follows:

(1) The flow potential of the sediment gravity flow significantly varies according to the initial soil state (solid; liquefied; fluidized or suspended). The flow potential markedly increases due to liquefaction (complete loss of effective stress) and to the reduction of the volumetric concentration in the regime of fluidized sediments.

(2) The internal structure of the fluidized sediment gravity flow distinguishes itself from that of the suspension-dominant gravity flow. The former may be characterized by the progressive formation of solidification zone, with virtually no or little settling behaviour.

(3) The fluidized sediment gravity flow can decelerate and undergo an abrupt stop due to progressive solidification. This emphasizes the two-phased nature of the fluidized sediment, which may reestablish a grain-supported framework during flowage through progressive solidification.

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