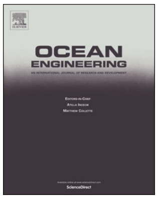
Ocean Engineering 109 (2015) 419–429

Contents lists available at ScienceDirect

Ocean Engineering

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



Centrifuge modeling and analysis of submarine landslides triggered by elevated pore pressure

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ARTICLE INFO

Article history:
Received 6 June 2015
Accepted 13 September 2015

Keywords:
Submarine landslide
Triggering mechanism
Elevated pore pressure
Gas hydrate dissociation

ABSTRACT

Understanding triggering mechanisms of submarine landslides is of great importance in view of the high risk they cause to human beings and facilities in the sea. Submarine landslides triggered by elevated pore pressures associated with gas hydrate dissociation were studied by centrifuge modeling and analysis of submarine slopes in saline water. Pressurized water was introduced into the sand to simulate the increased pore pressures caused by gas hydrate dissociation. The test results and analysis highlighted two mechanisms: (1) Accumulation of high pore pressure and associated tensile failure. Gentle slopes and thick clay favored the accumulation of pore pressure. Release of accumulated high pore pressure resulted in major pockmarks caused by tensile failure. Pore pressures at failure were up to 2.2 times the vertical effective stress of soil. The failed mass was intact and showed low mobility. (2) Fracturing in clay and associated shear failure. Fractures readily formed in steep slopes or thin clay during its downward movement, enabling the dissipation of pore pressure. The accumulated pore pressures at failure were close to or less than the vertical effective stress of soil. The failed mass was liquefied and attained high velocity due to mixing with water.

1. Introduction

A submarine landslide is initiated when the stress due to gravitational or earthquake forces exceeds the strength of the sediments, causing movement along one or more rupture surfaces. Submarine landslides may generate tsunamis that pose a threat to coastal populations. Exploitation of ocean floor resources is also affected through mass movement and subsequent sediment flow (e.g. Hampton et al., 1996; Locat and Lee, 2002; Watts and Grilli, 2003; Elverhøi et al., 2005; Masson et al., 2006; Tappin, 2010; Sassa and Sekiguchi, 2011; Boukpeti et al., 2012; Talling et al., 2015). Submarine landslides occur in a variety of geological settings. They are exceptionally difficult to monitor and great uncertainties are involved in the whole process. Understanding the triggering mechanisms of submarine landslides is of great importance in view of the high risk they pose to people and to facilities in the sea.

Submarine slope failure often occurs on low gradients, indicating that high excess pore pressures must be involved (Smith et al. 2013; Talling et al., 2014). This may result from gas hydrate dissociation, earthquakes, glacial loading or rapid accumulation of low-permeability sediments. Gas hydrates are ice-like compounds mainly consisting of methane and water. They have been identified offshore Canada, Japan, New Zealand and the United States (Collett, 2000). They are stable at the temperatures and pressures normally found on the seabed. When the temperature rises or the pressure drops, they become unstable and dissociate, resulting in the loss of solid material, discharge of free gas and increased fluid pressures. Studies have reported that gas hydrate dissociation may have contributed to historic submarine landslides (e.g. Paull et al., 1996; Huhnerbach and Masson, 2004; Mienert et al., 2005; Lee, 2009).

Dissociation of gas hydrate generally affects the stability of submarine slopes in two ways: (1) by forming weak layers in the sediments, and (2) by increasing excess pore pressure in the sediments, thus reducing their effective strength (Kvalstad et al., 2005; Masson et al., 2006; Grozic, 2010). Theoretical and experimental investigations have been conducted to identify strength variation of sediment caused by gas hydrate dissociation (e.g. Sultan et al., 2004; Xu and Germanovich, 2006; Nixon and Grozic, 2007; Winters et al., 2007; Lu et al., 2008; Zhang et al., 2012; Zhang et al., 2014). Numerical modeling has been reported to be a promising and powerful tool in evaluating the stability of submarine slopes and offshore structures (e.g. Biscontin and Pestana, 2006; Zhang et al., 2007; Brune and Ladage, 2010; Wang et al., 2010; Zhang et al., 2010; Sassa and Sekiguchi, 2011; Gao et al., 2013). Physical modeling also plays an important role in understanding submarine landsides and for interpreting field observations and evaluating the influence of such events on offshore structures (e.g. Gao et al., 2012; Talling et al., 2015).

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http://dx.doi.org/10.1016/j.oceaneng.2015.09.020
0029-8018/

Boylan et al. (2009) reported modeling techniques for triggering a submarine landslide in a geotechnical centrifuge at the University of Western Australia and for measuring the interactions between the runout material and the seabed. Gaudin et al. (2009) developed a wireless high-speed data acquisition system to monitor underwater mass movement in geotechnical centrifuge model tests. Yamada et al. (2010) performed a series of sandbox experiments simulating submarine landslides using a digital image correlation technique. They classified submarine landslide failures into two types: small but frequent slides, and large but less frequent failures of the entire slope, the small slides being precursors of major (large) failures. Yamada et al. (2010) also divided the failure process into four stages: pre-failure, lower slope steepening, small frequent slides, and large less frequent failure.

Truong et al. (2010) used electrical resistance profile, ultrasonic wave reflection imaging and shear wave geotomography to monitor submerged mass movements in 1 g models. Sue et al. (2011) described a two-dimensional model consisting of a rigid block sliding down a 15° slope, to compare physical and numerical models of tsunami generation caused by slides. Zakeri et al. (2012) and Zakeri and Hawlader (2013) conducted centrifugal experiments and numerical analyses to investigate the drag forces imposed on suspended pipelines by submarine slide blocks or out runner blocks. Zhao et al. (2013) described modeling techniques for simulating weak layers and elevated pore pressures in sediments in a geotechnical centrifuge, and discussed the effectiveness of the methods. Sahdi et al. (2014) examined the loading on a pipeline caused by an active slide by dragging a model pipe at different velocities through fine-grained soil in a centrifuge.

Usually a submarine mass failure may include consecutive phases, i.e. slide, debris flow and turbidity flow (Nisbet and Piper 1998). This paper focuses on the slide and its potential of mobility. Centrifuge modeling technique is used to investigate submarine landslides triggered by elevated pore pressures associated with gas hydrate dissociation in sloping submarine sediments consisting of a kaolin clay layer overlying a sand layer in saline water. Pressurized water was introduced into the sand layer to simulate the elevated pore pressures and facilitate accurate measurement of pore water pressures. The clay functioned as a low-permeability cover that trapped excess pore water pressure, thus triggering submarine landslides. Failure mechanisms were observed and interpreted in terms of slope angle, clay thickness and excess pore pressure accumulation.

2. Centrifuge models

2.1. Scaling law of centrifuge modelling

A geotechnical centrifuge has the ability to model complex behavior of soils under prototype stress levels (Taylor, 1995). The correct scaling relating to submarine landslide is essential for similitude of the processes in the centrifuge model and the prototype. The centrifuge scaling relationships for the problems concerned are summarized in Table 1. Conflict of time scale often rises with processes of pore pressure generation and dissipation which have time scales of N and N^2, respectively. For each model test, the pore water pressure was applied by steps. Each step was imposed instantly. The pore pressure elevating was considered to be the governing process. Therefore the time scale of N, as shown in Table 1, was used for the study to interpret test results.

Two approaches have been used to resolve the time-scale conflicts. One is to use an artificial viscous pore fluid (Lee and Scholfield, 1988) and the other is to use a soil with smaller coefficient of permeability (Kutter and James, 1989). The latter concept was incorporated in this study. The centrifuge tests were carried out with 1:50 scale models, e.g. the models were run at 50 g. The geometric scale factor was $N=50$. The Kaolin clay, with a permeability of lower than $1{*}10^{-9}$ m/s (Table 2), simulated a soil with permeability 50 times higher, i.e. $5{*}10^{-8}$ m/s. The requirement of time scaling can be satisfied by this way. With the scaling law, the physical process can be scaled to field scale.

Table 1
Centrifuge scaling relationships for submarine landslide.

Parameter	Model/prototype ratio
Macroscopic length$l$(L)	$1/N$
Gravity g (L/T^2)	N
Microscopic length d (L)	1
Fluid density ρ_f(M/L^3)	1
Fluid viscosity μ (FT/L^2)	1
Time t (T)	N
Average interstitial fluid velocity ν (L/T)	N
Reynolds number $\rho_f \nu\ d/\mu$	N

N=scale factor, L=length, T=time, F=force, M=mass.

Table 2
Properties of medium sand and kaolin clay.

Parameter		Value
Specific gravity of kaolin clay		2.7
Dry density of sand (kg/m^3)		1140
Permeability of saturated kaolin clay (m/s)		$<1{*}10^{-9}$
Shear strength of saturated kaolin clay in fresh water	Cohesion c_{cu} (kPa)	12
	Friction angle φ_{cu} (°)	18
Shear strength of saturated kaolin clay in saline water	Cohesion c_u (kPa)	8.6
Specific gravity of sand		2.65
Dry density of sand (kg/m^3)		1600
Permeability of saturated sand (m/s)		$1{*}10^{-4}$
Effective shear strength of sand	Cohesion c' (kPa)	0
	Friction angle φ' (°)	35
Shear strength at interface of clay and sand	Cohesion c' (kPa)	4.7
	Friction angle φ' (°)	28

2.2. Simulation of elevated water pressure

The centrifuge tests were carried out on the 50 gt centrifuge at Tsinghua University (Pu et al., 1994). The maximum load for the centrifuge is 1000 kg at a centrifugal acceleration of 50 g. Fig. 1a shows a strong box with inner dimensions 600 mm × 200 mm × 500 mm high. A submarine slope consisted of a layer of light grey kaolin clay 25–37 mm thick overlying a 15 mm thickness of medium-grade sand. At the target centrifugal acceleration of 50 g, the prototype thickness of clay ranged between 1.25 and 1.85 m, as listed in Table 2. The properties of the clay and sand are summarized in Table 2.

The tiltable base was made of impermeable Plexiglass plate in the form of a shallow rectangular tray (inner dimensions 170 mm × 470 mm × 15 mm deep) to retain the sand. Fig. 1b shows details of the arrangement of sensors on the plate, which was hinged at its lower end to enable its slope angle to be altered. The angle of the plate was adjusted at 1 g to form slope angles of 15°, 20° and 25°. Grooves prefabricated in the plate held 4 mm diameter rubber tubes. The tubes and their outlets were glued in the grooves so that they would not hinder soil movement. The base of the tray was flat after installing the tubes. Thirteen outlets allowed the introduction of pressurized water into the soil from a water tank mounted on the centrifuge.

The clay and base plate were designed to simulate low-permeability sediments containing gas hydrate which, when dissociated, caused excess pore pressure to accumulate in the sediment. Three pore water pressure transducers (PPT) 6 mm diameter × 12 mm long (P_1–P_3, Fig. 1c) were positioned in the sand to monitor variation