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Analysis of the Motion and Dynamic Characteristics of Subaqueous Debris Flows

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Abstract

Subaqueous debris flow is one of the most important marine geological disasters. Understanding the subaqueous debris flow is related to the safety of marine engineering and the development of the national economy. In this paper, the subaqueous debris flow is taken as the research object. Through a comparative study of terrestrial debris flow, combined with existing research results, the characteristics, motion characteristics and motion dynamics of subaqueous debris flow are studied, and the future research direction of subaqueous debris flow is discussed. The study shows that the water pressure during the motion process of subaqueous debris flow can not be ignored. Physical model test and numerical simulation are the most important research methods at present. How to accurately measure the parameters of the motion process in the physical model test is a difficult problem. In the numerical simulation, the constitutive model and the coupling of multiphase medium need to be further studied. A large number of measured data, physical experiments and numerical simulation data remain to be accumulated. It is a direction to study the kinetic theory of subaqueous debris flow from the point of view of plastic fluid mechanics and energy conversion.

Keywords: subaqueous debris flow, flow characteristics, motion process, velocity, impact force

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INTRODUCTION

Along with the development of science and technology, people's ideology has been promoted. The development of marine resources, especially the investigation and development of offshore oil resources and the construction of seabed engineering has been increasing. The construction of operation area and engineering facilities are slowly moving to the deep water area. But the construction of various facilities, such as submarine cables, submarine oil and gas pipelines, and so on, is very vulnerable to the impact of marine geological disasters (Hsu et al. 2009, Nadim and Locat 2005, Tappin et al. 2001). And once they are affected, most of them are irreversible and can't be repaired again. So people pay more and more attention to the engineering geological conditions and marine geological hazards on the seabed. The instability of the seabed slope is one of the main concerns. Now many scholars have studied the mechanism and the characteristics of the failure of the submarine slope instability. Relative to the land-based geological disasters, the related research on marine geological disasters has just started, and the research is very superficial. However, with the deepening of research and the continuous development of seabed resources and the new territory of the seabed, this study will have a very important national strategic significance.

The classification of slope instability on land is more detailed. However, because of the limitation of detection means, the study on the classification of submarine slope instability is not enough. Dott (1963), Moore (1979), Locat et al. (2002), Canal et al. (2004) and Xian et al. (2017) categorized the instability of the seabed slope. Although the names are different, the subaqueous debris flow is expressed in various classifications, mainly refers to the flow of material flow in the instability of the slope, which belongs to the debris flow, mudslides and turbidity. It is an important process for handling long-distance clastic sediments, and is a main type of submarine slope failure. It not only greatly affects the ecological environment of the deep sea, but also has great destructive power to the submarine pipelines, cables and other artificial facilities, and even causes tsunamis (Zakeri et al. 2008, Zakeri 2009, Randolph and White 2012). However, due to the limitation of observation conditions and investigation technology, the research process of subaqueous debris flow has been lagging behind the land debris flow research. With the development of technology and the application of high-end instruments, people have a new

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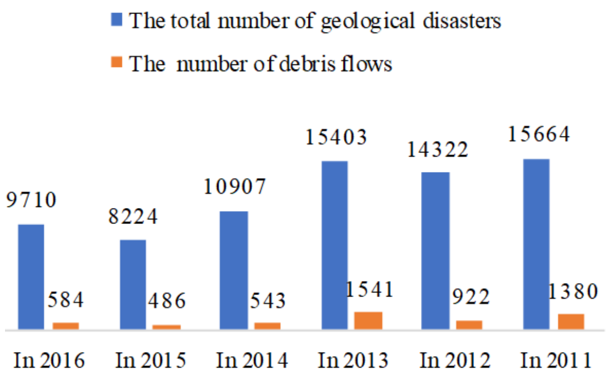

Fig. 1. Statistical table of frequency of debris flow in China from 2011 to 2016

understanding of subaqueous debris flow, and further research can be done.

In this paper, the subaqueous debris flow is taken as the research object. Through comparative study of terrestrial debris flow, combined with existing research results, research on the characteristics, motion characteristics of subaqueous debris flow and dynamics of debris flow are studied, the problems of research on the theory, technology and method of subaqueous debris flow in the future are discussed.

CHARACTERISTICS OF SUBAQUEOUS DEBRIS FLOW

Debris flow is a disastrous geological phenomenon, which is a high-concentration fluid composed of sediments and rocks mixed with water. Terrestrial debris flow is very common. For example, debris flow geological disasters in China are second only to landslides and collapses as shown in **Fig. 1** (from 2011-2016 China National Geological Disaster Bulletin (Ministry of Land and Resources of the People's Republic of China 2011-2016)). Many scholars have carried out a great deal of research on terrestrial debris flow from aspects of formation conditions, starting mechanism, kinematics, monitoring and early warning, risk assessment and project management. Many achievements have been made and consensus has been reached in many aspects.

Subaqueous debris flow is a large-scale, high-density, high-volume flow of seabed sediment that occurs in water under gravity or other loads at high velocity along slopes and is also known as turbidity. It belongs to gravity flow or high-density stream. Compared with terrestrial debris flow, subaqueous debris flow usually occurs in submarine canyons such as sedimentary fans, estuarine delta and open continental slope. Submerged sediments have large void ratios, low shear strength, and are susceptible to perturbation and movement. Subaqueous debris flow is usually subdued at low angles of typically 3-4%. Debris from terrestrial debris flow is a product of terrestrial sedimentary environment that consists primarily of gravel and clay particles of various sizes. Clay particles are cohesive and join the gravel to a mixture of earth and rock. The material source of subaqueous debris flow is the product of marine sedimentary environment, which is dominated by sand particles and has no adhesion and good sorting. Studies show that there are usually two types of subaqueous debris flow: one is unstable sediment on the margins of the coastal continent or seabed, and debris flow is formed by the triggering action. The other is the subaqueous slide failure, in the process of sliding, the shape and volume of slide continue to change by the water flow resistance and erosion, the volume is growing, and gradually develop into a high-density fluid carrying mud, sand, and even gravel (Jiang 2010). The trigger of terrestrial debris flow is mainly heavy rain, which provides sufficient water source, and then carries a large amount of loose debris washed down from the valley gully, causing mud-rock flow disaster. The triggers of subaqueous debris flow are mainly earthquakes, submarine volcanoes and storm surges (Hance 2003, Zhang 2016). The shelf-glacier activities and self-weighting are also the causes of subaqueous debris flow (Stoecklin et al. 2017).

In general, the marine environment is much more complex than the terrestrial environment. Because of the research means and the importance of the research, the research on subaqueous debris flow started relatively lately at home and abroad and is still in the initial stage. Compared to the study of terrestrial debris flow, the formation conditions, starting mechanism, or kinematic characteristics of subaqueous debris flow have not reached a consensus, more advanced technology and research efforts need to be input.

RESEARCH ON THE MOTION CHARACTERISTICS OF SUBAQUEOUS DEBRIS FLOW

At present, research on subaqueous debris flow has just started. Due to the limitation of environmental conditions and technical conditions, it is still difficult to directly observe the motion process of subaqueous debris flow. Therefore, physical model test is still an effective method to study subaqueous debris flow (Hu et al. 2006, Li et al. 2012). As for physical model tests, Mohrig et al. (1998) adopted adjustable-angle glass-wall flume and set up soft and hard floor materials to simulate the flow of debris flow respectively. The experiment found obvious “hydroplaning”, providing a powerful explanation for the low-angle and long-distance migration of submarine landslides. Laval et al. (1988) conducted a similar tank test using low-density sand and found that there was a thin layer of water between the front of the sand flow and the bottom of the tank, and the phenomenon of “hydroplaning” occurred. Marr et al. (2001) specifically analyzed the impact of clay and water content on the flow characteristics of mud and found that when the clay content is high, the mud exhibits laminar flow with plastic rheological properties. As the clay content decreases, sliding mud ends are more and more prone to fracture. Elverhoi et al. (2010) compared the results of mud simulations of clay contents of three different grades - high (25%), medium (15%) and low (5%). At higher levels, the soil can travel far distances at high velocity with the hydroplaning effect, even at very small slopes. As the sand content increases, the viscosity of the fluid decreases, causing the internal particles to separate and form a double-layer flow, where the upper layer is a low-density layer of fine clay and silt and the lower is high-density. Vendeville et al. (2003) used high-porosity sand, clay and viscous silicon polymers to simulate landslides and analyzed the triggering conditions of pore pressure and slope angle on submarine landslides. It was found that fluid pressure can effectively trigger submarine landslides. Based on previous experimental schemes, Ilstad et al. (2004) found that the flow velocity of debris flow is relatively low when the viscosity is high and the flow velocity decreases gradually from the end to the rear, while the flow velocity of the debris flow is relatively uniform when the viscosity is low, and then obtained the “detachment” of front debris flow coincided with the practical. Zakeri et al. (2008) used a sink test to simulate the impact of subsea landslide debris flow on submarine pipelines, and proposed a method to estimate the drag force of debris flows when impacting the pipeline. Zhang et al. (2002) analyzed the turbidity fluid motion process through experiments, the thickness decreased gradually, the velocity increased slowly from the slow increase. Yang (2012) used a large drum centrifuge to prove that the larger the water content of landslide, the greater the sliding velocity. Acosta et al. (2017) used cartridge centrifuges to study the water content of subaqueous debris flow when hydroplaning occurs, indicating that the water content level has an influence on the formation of hydroplaning, altering the values of fluid pressure, normal stress and densimetric Froude number. For sand and clay mixtures, “hydroplaning” effect is only possible when the moisture content is above the liquid limit.

Experiments have shown that in the water flow process, the slurry head was observed significantly upward gradient, mud and turbidity separation process was very long. After a while, the high-density layer was settled, and only the upper low-density layer was still moving. Clay content is the most important factor affecting the migration characteristics of mud. The higher the clay content, the greater the viscosity, the more obvious the plastic rheology, the greater the migration distance. The lower the clay content, the lower the viscosity, the more uniform the overall flow velocity of the slurry body and the smaller the migration distance. Sliding surface angle is another factor affecting the migration law of slurry. Even if the sliding surface angle is very small under water, the slurry can be transported far away by “hydroplaning effect” and have a great impact force and destructive force.

With the continuous improvement of computer performance, meshless method has gradually become one of the main methods to solve the issue of large deformation. Because it is based on discrete point approximation, it is not necessary to use grid, thus solving the grid distortion problem of finite element method and finite difference method in solving large deformation problems, providing a new idea for simulating the motion process of subaqueous debris flow. In numerical simulation, Gue (2012) used DAMPM model to simulate the landslide sliding process, which is better than the centrifuge test results. Zakeri et al. (2008) calculated the flow direction of the debris flow and the force acting on the surface of the pipeline by the debris flow through the numerical analysis of the corresponding model tests and computational fluid dynamics (CFD). Zakeri (2009) used CFD numerical software to simulate the impact force of mud on submarine pipelines under different impact angles, which supplemented the deficiencies of previous studies. Liu (2016) used CFD software FLUENT to simulate the generalized landslide into the water and subaqueous motion process, and obtained the law of the water resistance of the landslide under water. Based on the small-scale numerical model of non-Newtonian Euler-Euler two-phase theory, Xiu et al. (2016) simulated and analyzed the impact of material composition, topographic gradient, initial velocity and initial thickness on the motion characteristics of the submarine landslide movement. However, the meshless method has some inherent defects. The approximate functions of the meshless method are generally complex, and most do not have the interpolation property. When the number of particles is large, the computational cost is too large.

To sum up, a lot of work has been done by scholars at home and abroad on the research of motion characteristics of subaqueous debris flow. Many useful methods and conclusions have been explored and put forward. However, scholars mostly focus on the study of the status of debris flow migration, and the migration laws of subaqueous debris flow are rarely systematically summarized. Meanwhile, as for the physical model tests, most scholars use subsided mudslides to simulate subaqueous debris flow in the sink of a still water environment, neglecting the formation conditions of the subaqueous debris flow and the hydrodynamic factors of the ocean. The results of the study inevitably differ from the actual subaqueous debris flow. Therefore, how to simulate the occurrence of subaqueous debris flow more accurately and to measure the relevant parameters more accurately and effectively is the direction of the development of model simulation test. Numerical simulation will become an effective research method for subaqueous debris flow in the future. Multiphase flow theory has been introduced into simulations of submarine landslides in recent years. However, the rheological parameters in model simulations are mostly determined by experimental mud parameters obtained from a rheological experiment, and rheological parameters are constantly changing and unpredictable in the actual process. Therefore, numerical simulation needs further study on boundary conditions, rheological parameters, constitutive model and the coupling of multiphase medium.

RESEARCH ON THE MOTION DYNAMICS OF SUBAQUEOUS DEBRIS FLOW

The research of the kinematics of terrestrial debris flow mainly focuses on the mechanism of mechanical model transformation in debris flow process and the dynamic characteristics of debris flow fluid. The same applies to subaqueous debris flow. However, there are still few studies on the dynamics of subaqueous debris flow.

As for the mechanics model transformation mechanism in the motion process of subaqueous debris flow, scholars did research from the field of fluid dynamics. Imran et al. (2001) simulated debris flows using the Hershel-Bulkley and bilinear rheology models, which did not account for the "hydroplaning" phenomenon and did not correspond to some of the experimental results. Based on the lubrication theory, Harbitz et al. (2003) proposed a one-dimensional analytical model under steady "hydroplaning" conditions. The upper fluid was simplified as a rigid body and the bottom was a water layer with a linear change in thickness. The vertical velocity was assumed to be a parabolic distribution. The model ignores hydrodynamic pressure at the front, tail and top, and studies have shown that hydrodynamic pressure is very important. On the basis of Imran et al., De Blasio et al. (2004) proposed an improved viscous rheological model that divides the flow of debris flows into four phases, the initial flow, producing water wedge, "hydroplaning", "hydroplaning" stop. The model is in good agreement with the experiment, but the parameters of critical Froude number, initial wedge shape, debris flow and seabed roughness are supposed, and further research is needed. Based on the theory of dynamic lubrication, Wright et al. (2004) established a two-dimensional viscous rheological model to simulate the flow deformation of the debris flow process. At present, the theoretical models proposed by scholars have their own shortcomings. Moreover, the verification is complicated, and the direct relationship between the physical quantities can not be given, which limits the application of the theoretical models. How to apply the theoretical model to the actual simulation of large-scale subaqueous debris flow is also the direction of further research.

The most important dynamic characteristics in the motion process of subaqueous debris flow are the flow velocity, impact force and distance, which are indispensable parameters in the design of debris flow hazard assessment and control engineering. For debris flow motion process and kinematic parameters, scholars mainly study through physical experiments and numerical simulation. Breien et al. (2007) conducted a physical model test on different sand and clay hybrid materials and monitored them using the PIV (Particle Image Velocimetry) technique, compared the onshore debris flow with the subaqueous debris flow and investigated the dynamical behavior of subaqueous debris flow. Through the study of subaqueous turbidity, scholars believe that the average flow velocity of turbidity is roughly proportional to the original slope of seafloor topography, the density of water bodies and the depth of water. Based on a series of experimental studies on subaqueous debris flow and land-based use, Yu (2007) proposed the relationship between subaqueous debris flow velocity and terrestrial debris flow velocity under the same conditions (e.g. same bed roughness, debris flow test material, etc.). Due to the difficulty of accurately measuring the thickness of the subaqueous debris flow movement during simulation experiments on subaqueous debris flow, it is difficult to accurately measure the velocity of the debris flow. Due to the low field data and the contrastive data of subaqueous and terrestrial debris flow with the same true parameters, the kinematic velocity formulas of subaqueous debris flow proposed by scholars are still few.

For the study of impact force on subaqueous debris flow, scholars focused on the impact force of subaqueous debris flow or submarine landslide on submarine pipelines, such as Zakeri et al. (2008), Zakeri (2009) and Xiu et al. (2016) mentioned above. Dong et al. (2017) used the material point method (MPM) with an enhanced contact algorithm. The Herschel-Bulkley rheological model is incorporated to reflect the dependence of the undrained shear strength of the sliding mass on the shear strain rate. The impact velocity, impact force formula, and the correlation coefficient calculation formulas of subaqueous debris flow against submarine pipelines under different pipe diameters and initial height of subaqueous debris flow are studied. In general, the research on impact force on subaqueous debris flow is an important issue in the dynamics of subaqueous debris flow and is the direct cause of project damage. It is related to the size and stiffness of the impacted member, and due to the uncertainty of material composition and particle size distribution in subaqueous debris flow, it brings many difficulties to the research of impact force on subaqueous debris flow. It may be one direction to study the movement of subaqueous debris flow from the point of view of plastic fluid mechanics and energy conversion. In addition, the inherent laws of measured data and laboratory tests should be analyzed.

CONCLUSIONS

This work addressed the characteristics of subaqueous debris flow, motion characteristics of subaqueous debris flow and dynamics of debris flow. Based on the summary and analysis of existing research results, the following conclusions and discussions can be drawn.

1. Although there are similarities between the movement of subaqueous debris flow and terrestrial debris flow, there are also significant differences. On the one hand, due to the different sedimentary environment of the ocean, which mainly consists of sand and clay, the porosity ratio is large and is usually in a saturated state, and the soil is in a state of weak gravity. On the other hand, subaqueous debris flow is in contact with the liquid phase and is subjected to hydrodynamic pressure. In the motion process, "hydroplaning", soil-water dispersion and other phenomena can occur. As a result, the head of subaqueous debris flow was observed significantly upward gradient, mud and turbidity separation is also observed. After a while, the high-density layer was settled, and only the upper low-density layer was still moving. In general, subaqueous debris flow is transported far and has great impact force and destructive power. Currently, the main factor affecting the motion process is the clay content in the debris flow.
2. Physical model test and numerical simulation are the most important means to study the law of the motion process of subaqueous debris flow and also an important way to verify the theoretical model and calculation formula. According to the study of debris flow movement, how to accurately measure various parameters in motion process is a difficult problem in physical model simulation. Drum centrifuge is a very effective test equipment, and large physical model tests can make the simulation process closer to reality and obtain more accurate simulation results, this is a direction of future efforts. In the field of numerical simulation, multiphase flow theory has been introduced into simulations of submarine landslides in recent years. Numerical simulation needs further study on boundary conditions, rheological parameters, constitutive model and the coupling of multiphase medium.
3. The research on mechanical model transformation mechanism in the debris flow motion process, dynamic characteristics of debris flow fluid and the kinetic theory is still relatively less. The rheological models proposed by scholars have their own shortcomings, the shear strength and bulk density of subaqueous debris flow in the motion process are gradually low, and the material is also changing. It is a direction to study the movement of subaqueous debris flow from the point of view of plastic fluid mechanics and energy conversion. A large number of measured data, physical experiments and numerical simulation data remain to be accumulated, so as to quantitatively study the

velocity, impact force and moving distance of subaqueous debris flow.

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