

Experiment and analysis of the formation, expansion and dissipation of gasbag in fine sediments based on pore water pressure survey

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Abstract

Deep-seated gas in seabed sediments migrates upwards from effect of external factors, which easily accumulates to form gasbags at interface of shallow coarse-fine sediments. Real-time monitoring of this process is important to predict disaster. However, there is still a lack of effective monitoring methods, so we attempt to apply multi-points pore water pressure monitoring technology when simulating forming and dissipation of gasbags in sediments through laboratory experiment. This study focuses on discussion of sensitivity of pore water pressure monitoring data, as well as typical changing characteristics and mechanisms of excess pore water pressure corresponding to crack generation, gasbag formation and gas release. It was found that the value of excess pore water pressure in sediments is negatively correlated with vertical distance between sensors and gas source, and the evolution of gasbag forming and dissipation has a good corresponding relationship with the change of excess pore water pressure. Gasbag formation process is divided into three stages: transverse crack development, longitudinal cavity expansion, and oblique crack development. Formation of gasbag begins with the transverse crack at the interface of coarse-fine sediments while excess pore water pressure attenuates rapidly and then drops, pressure remains almost unchanged when cavity expands longitudinally, oblique crack appeared in final stage of gasbag evolution while excess pore water pressure accumulated and dissipated again. The variation curve of excess pore water pressure in gas release stage has saw-tooth fluctuation characteristics, and the value and time of pressure accumulation are also fluctuating, indicating the uncertainty and non-uniqueness of gas migration channels in sediments.

Key words: pore water pressure monitoring technology, excess pore water pressure, gasbag, cracks, gas migration

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1 Introduction

The gas of different causes is common in marine sediments (Fleischer et al., 2001). Changes in the balance of geological environment (Johnson et al., 2019), external forces or disturbances of marine engineering construction (Lu et al., 2019) may induce the upward escape of deep-seated gas. The gas is easy to accumulate to form a gasbag when it migrates to the bottom interface of shallow fine-grained sediments (Koch et al., 2015). As the gas accumulates and the gas pressure rises, the overlying sediments layer domes, the gas escapes, and eventually the overburden is destroyed, which may lead to geological disasters such as pockmarks (Boudreau, 2012; Yan et al., 2020), mud volcanoes (Blouin et al., 2019), plumes (Judd and Hovland, 1992) and even landslides (Vanneste et al., 2014).

Obviously, it is necessary to *in-situ* monitor the gasbag evolution process to assess the environmental and geological disaster effects. Domes have been shown in many acoustic surveys

(Duarte et al., 2007; Savini et al., 2009; Passaro et al., 2016; Wang et al., 2018), however, the research on acoustic surveys does not have a clear understanding on formation and evolution of gasbags, and gas pressure inside the gasbag cannot be obtained. The resistivity probe can monitor the change of gas content within a limited area which depends on the thickness of the probe (Bi-anchin et al., 2011; Demuth et al., 2015), but the monitoring range is small and it is difficult to locate accurately in *in-situ* monitoring applications. Theoretically, the thin plate elasticity can be calculated as the total overpressure required for the formation of gasbags and causing domes (Barry et al., 2012), but the model is suitable for cases when the thickness of overlying sediments is much smaller than the radius of domes. The calculation error is large when the overburden is thick or the radius of domes is small. In a word, there is no mature method to achieve real-time and *in-situ* monitoring of gasbags currently.

Pore water pressure monitoring is often used in *in-situ* obser-

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variations on the seafloor (Sultan et al., 2009; Vanneste et al., 2014). Since it is sensitive to the changes in the stress state and stability of sediments, pore water pressure can reflect fluid changes in sediments within a certain range basing on its “remote sensing” capability (Lu et al., 2019). Generally speaking, the increase in gas volume will cause the expansion of fluid volume. In poorly permeable fine-grained sediments, the volume expansion will be converted into excess fluid pressure when fluid flow and expansion are restricted (Kwon et al., 2008), resulting in the generation of excess pore water pressure (Liu et al., 2020). Over-high pore water pressure leads to the growth of cracks (Xu and Germanovich, 2006; Zhang et al., 2015b; Rocco et al., 2017), which bring about the dissipation of gas. Research on bubble-induced cracks in microscopic experiments has been shown that gas breakthroughs in sediments are accompanied by significant changes in pore water pressure (Graham et al., 2016), while the periodic discharge of gas corresponds to the periodic increase and decrease in pore water pressure (Acharya et al., 2016). Previous studies have shown that changes in excess pore water pressure are directly related to gas sources (gas flow, gas pressure, etc.) and sediment permeability (Xu and Germanovich, 2006).

In this article, the pore water pressure monitoring method is used to do multi-points monitoring through a laboratory model experiment simulating the process of gasbag generation and growth, gas escape, and gasbag dissipation in fine-grained sediments. The analysis and discussion focus on the effective range of pore water pressure monitoring, the typical characteristics of excess pore water pressure changes in crack formation, gasbag growth and gas release. Meanwhile, the relationship between research findings and application on *in-situ* pore water pressure monitoring is discussed. The goal of this work is to explore an effective *in-situ* monitoring technology to realize the monitoring and pre-warning of gassy disasters.

2 Methods

2.1 Sediments collection and characterization

The fine-grained sediments used in the experiment is silt collected from the Yellow River Estuary of China (April 2018, 37.3°N, 118.3°E). A fine screen with an aperture of 0.1 mm is used to remove impurities (e.g., shells, leaves) in sediments. A laser

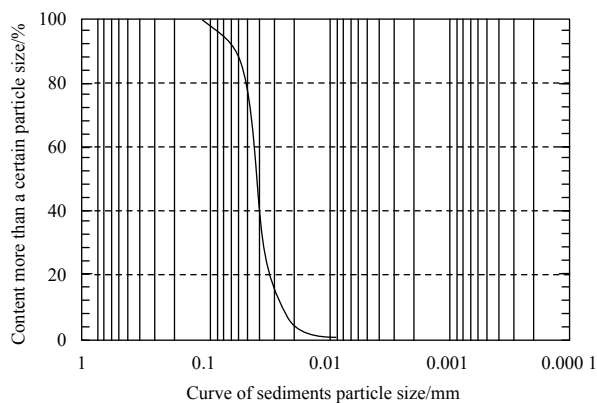


Fig. 1. Cumulative probability curve of silt.

particle size analyzer (Winner2000E) is used to determine sediments particle size distribution (Fig. 1). The fine-grained sediments is milled fully using wooden rods in advance. After adding seawater, a high-speed mixer supplying shear stress, which broke the structure between particles and made the sample fully infiltrated, is applied to the silt for preparation of homogeneous slurry. The prepared saturated silt is measured basic physical and mechanical parameters based on “Soil Test Regulation SL-237-999” (Table 1). The coarse-grained sediments is medium sand with a particle size distribution between 0.25 mm to 0.5 mm ($\rho=1.73 \text{ g/cm}^3$, $e=0.50$, $K=3.4 \times 10^{-2} \text{ cm/s}$).

2.2 Experimental system

The experiment is carried out in an acrylic model box whose size is 800 mm×400 mm×500 mm and the thickness of plexiglass is 20 mm. The seawater layer is set to 30 mm to simulate underwater environment and facilitate to observe the bubbles release position. The thickness of fine-grained sediments layer is 130 mm, and the thickness of coarse-grained sediments is 210 mm to alleviate the disturbance of gas injection by air compression.

Four pore water pressure sensors (YSV3211, range 0–20 kPa, accuracy 0.5%) are pre-buried in sediments, of which 3 pore water pressure probes (P_1 , P_2 , P_3) are located perpendicularly above the gas injection port, the vertical distances from the surface of fine-grained sediments are 140 mm, 80 mm, and 20 mm respectively. As shown in Fig. 2, P_1 is within the coarse-grained sediments and near the interface of coarse-fine sediments, P_2 and P_3 are within fine-grained sediments. Another pore water pressure probe P_4 is buried in the same depth as P_2 , located in fine-grained sediments, 100 mm horizontally from the gas injection port. A DEVE-43A eight-channel data acquisition instrument is used in the experiment, and DEVESoftX software is used to read the electric signals. The main acquisition parameters include that the sampling frequency is 100 Hz per channel, the measurement type is bridge measurement, and the sample rate divider is an average of 2 times.

An air compression (550 W×3) is used to provide gas, and it was connected to a gas pipe and a precision pressure controller (IR2000-08BG, maintaining a stable gas pressure). The gas pipe was a hard rubber pipe with an external diameter of 8 mm and an interior diameter of 5 mm. The gas output from the air compressor was fed into the coarse sediments through five gas pipes linked with a gas shunt space, as shown in Fig. 3. Five gas pipes outlets were arranged closely in the center of bottom surface.

The rate of gas flow (Q) is about 1 L/min before the gas escapes from fine-grained sediments, and the gas pressure of the source controlling system is 10 kPa (P_1). After splitting, the gas pressure in the pipeline changes to 11.2 kPa (P_2). And the gas outlets were located at 370 mm below the water surface affected by the hydrostatic pressure (u_0) (3.7 kPa).

2.3 Experiment procedure

The sensitivity of pore water pressure sensors have been checked and then calibrated them before the experiment. The subsequent experimental operation includes: (1) laying the gas pipe, inpouring seawater, laying the coarse-grained sediments, and standing it for 24 h to saturate; (2) laying the silty slurry and consolidating naturally for 7 d; (3) opening the camera and the

Table 1. Basic physical and mechanical parameters of silt

Water content (ω)/%	Density (ρ)/ ($\text{g}\cdot\text{cm}^{-3}$)	Dry density (ρ_b)/($\text{g}\cdot\text{cm}^{-3}$)	Gravity (G_s)	Porosity ratio (e)	Plastic index (I_p)	Consolidation coefficient (C_v)/($\text{cm}^2\cdot\text{s}^{-1}$)	Permeability coefficient (K)/($\text{cm}\cdot\text{s}^{-1}$)	Undrained shear strength (C_u)/kPa
20.5	2.08	1.73	2.7	0.57	6.9	2.79×10^{-3}	1.66×10^{-5}	6

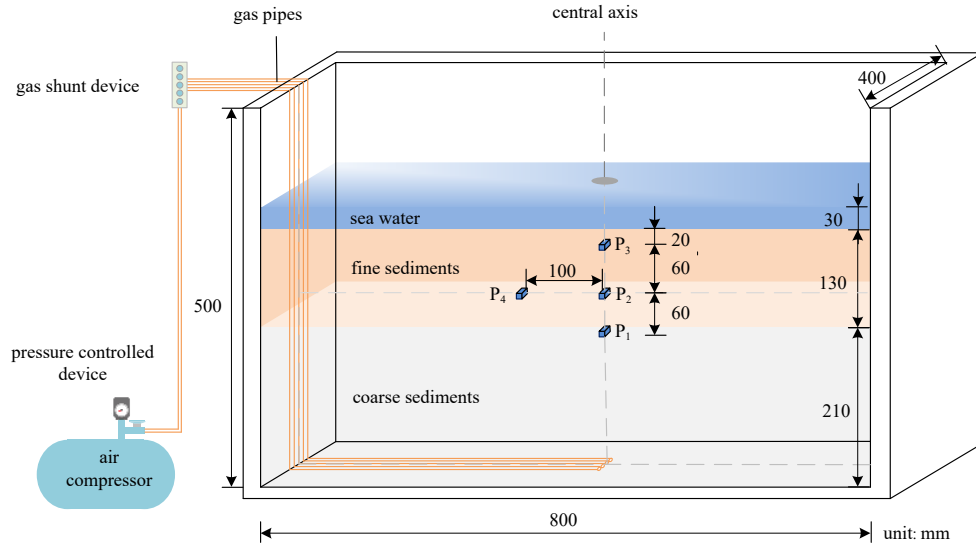


Fig. 2. Device layout. P_1 , P_2 , P_3 , and P_4 are pore water pressure sensors.

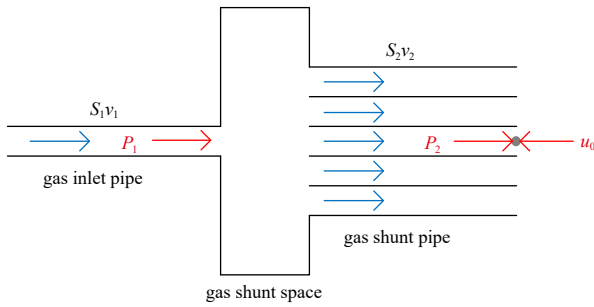


Fig. 3. Gas shunt. Blue arrow indicates gas flow direction, red arrow indicates pressure.

pore water pressure data acquisition instrument, then opening the air compression and the controlling valve to pump gas into the model box after the data is stable; (4) when the overlying fine sediments layer is significantly damaged or the gas escape velocity is stable, turning off all equipment and terminating gas injection. The collected data includes 300 s of background data before gas injection and 1 700 s of gas injection process data.

According to the calibration result (calibration formula) of pore water pressure sensors (the calibration formulas can be found in Appendix), the collected electrical signal data has been converted into pore water pressure data. Since the pore water pressure and the excess pore water pressure are a pair of essentially identical concepts, the excess pore water pressure could better reflect the part of the force undertook by pore water owing to an external force that the following data and discussion are based on the excess pore water pressure data. When the sediments are static without disturbance, the pore water pressure value is equivalent to the hydrostatic pressure value. The average value of background data can be taken as the hydrostatic pressure value. The value of excess pore water pressure is corresponding to the value of pore water pressure minus the value of hydrostatic pressure.

2.4 Numerical modeling of gas pressure changes in cracks

Cracks forms at the interface of coarse-fine sediments due to gas, and the migration ways of gas in fine-grained sediments is mainly in the cracks. To quantify the attenuation of gas pressure

in cracks, we have simplified the formation process of cracks into two models. One represents gas migrating from the coarse-grained sediments to the fine-grained sediments boundary to gather and then drainage to form cracks; another shows that the gasbag pressure increases to fracture the fine-grained sediments after the gas accumulates to form a gasbag, as shown in the Fig. 4. In order to simplify the calculation about the dynamic changing of gas pressure during the formation of cracks, we use a one-dimensional dynamic model to simulate. In this one-dimensional model, the velocity is regarded as a scalar that means the direction can be ignored.

In this model, we used mathematical parameter equations to simulate gas pressure changing in cracks. As time (t) changes, cracks gradually expand. M represents the quality of the water-gas mixture in the crack. The calculation method of M in this model is

$$M = M_0 - Q_w t + Q_g t, \quad (1)$$

where M_0 stands for the original mass in the cracks, Q_w represents the water mass flux in unit-time flowing from the cracks to

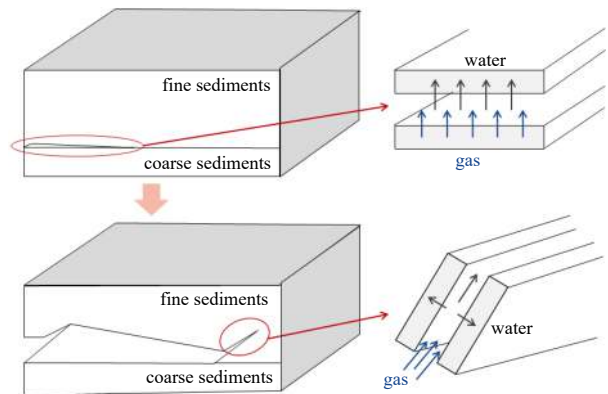


Fig. 4. Crack generation mode. The gray arrow represents water flowing out of the crack (from the fracture to the sediments), and the blue arrow represents the gas intrusion into the crack (from the sediments to the crack).

the sediments, and Q_g is the gas mass flux flowing into the sediments in unit-time. Q_w could be written as follows:

$$Q_w = \varepsilon_0 u_w S \rho_w, \quad (2)$$

in which S represents the cross-sectional area of the crack. ε_0 represents the initial porosity, with a value of 0.363, and ρ_w represents the density of water, with a value of 10^3 kg/m^3 . In this model, we consider water to be a homogeneous and incompressible fluid. u_w represents the water flow rate, which is closely related to the water permeability k_w of the cracks (value $1.66 \times 10^{-5} \text{ cm/s}$):

$$u_w = -\frac{\partial P_w}{\partial z} \frac{k_w}{\varepsilon_0 \mu_w}, \quad (3)$$

where the right side represents the change in pore water pressure (P_w) with the lateral distance z , and μ_w represents the viscosity of pore fluid (10^{-3} Pa/s). Comprehensive Eqs (2) and (3), the equations can be obtained as

$$Q_w = -\frac{\mu_w}{k_w} S \rho_w \frac{\partial P_w}{\partial z}. \quad (4)$$

For the gas mass flux part in Eq. (1), Q_g can be written as follows:

$$Q_g = \varepsilon_0 S \rho_g u_g, \quad (5)$$

in which ρ_g represents the gas density and u_g represents the gas velocity flowing from the deposit into the cracks. Because the density of gases (ρ_g) changes with the pressure P , the pressure flow density formula and the gas state formula are all used to solve the ρ_g and the pressure flow density formula is

$$Q = P + \rho_g S \Delta + \frac{1}{2} \rho_g u_g^2. \quad (6)$$

The gravity term of gas can be ignored, and Q is the flow flux of gas injected, with a value of $6.6667 \times 10^{-6} \text{ m}^3/\text{s}$. Thus Eq. (6) can be simplified as

$$Q = P + \frac{1}{2} \rho_g u_g^2, \quad (7)$$

$$\rho_g = \frac{2(Q - P)}{u_g^2}. \quad (8)$$

The volume occupied by gas per unit time in the cracks can be regarded as the volume V_w of the water flowing to the sediments. Therefore,

$$PV_w = nRT = \frac{Qt\rho_g}{M_{\text{mol}}} RT, \quad (9)$$

in which, R is a gas constant, $R=8.31 \text{ Pa}\cdot\text{m}^3/(\text{mol}\cdot\text{K})$; T represents Kelvin's temperature which values 293; n is the amount of substance; M_{mol} represents the molar mass of gas,

$$\frac{Q_w}{\rho_w} = V_w. \quad (10)$$

Therefore, the P is

$$P = \frac{Qt\rho_g}{M_{\text{mol}}} \frac{\rho_w}{Q_w} RT. \quad (11)$$

In Eq. (11), M_{mol} represents the molar mass of gas. Comprehensive Eqs (5)–(11), the equations can be obtained as

$$\rho_g = \frac{2 \left(Q - \frac{Qt\rho_g}{M_{\text{mol}}} \frac{\rho_w}{Q_w} RT \right)}{u_g^2}. \quad (12)$$

Therefore, the Q_g can be obtained as

$$Q_g = 2\varepsilon_0 S \frac{Q - \frac{Qt\rho_g}{M_{\text{mol}}} \frac{\rho_w}{Q_w} RT}{u_g}. \quad (13)$$

Lu et al. (2015) believe that the pressure of gas in cracks of the one-dimensional model can be regarded as

$$P_g = \rho_g a^2 = \frac{M}{S\Delta} a^2, \quad (14)$$

where a^2 represents the propagation speed of sound which changes with the medium, and Δ represents the width of the crack. In summary, comprehensive the all above formula, P_g can be obtained as

$$P_g = \frac{M_0 - Q_w t + Q_g t}{S\Delta} a^2 = \left[M_0 + \frac{\mu_w}{k_w} S \rho_w \frac{\partial P_w}{\partial z} + 2\varepsilon_0 S \left(\frac{Q - \frac{Qt\rho_g}{M_{\text{mol}}} \frac{\rho_w}{Q_w} RT}{u_g} \right) t \right] \frac{a^2}{S\Delta}. \quad (15)$$

Meanwhile, when $t=0$, the initial conditions can be found as follows:

$\varepsilon_0=0.363$, $\rho_w=10^3 \text{ kg/m}^3$, $k_w=1.66 \times 10^{-5} \text{ cm/s}$, $\mu_w=10^{-3} \text{ Pa/s}$, $Q=6.6667 \times 10^{-6} \text{ m}^3/\text{s}$.

The other parameters' value and the timescales of the spin up stage in the model would be defined according to the experiment, and the results can be found in Section 3.2.

3 Results and discussion

3.1 Data and response sensitivity of excess pore water pressure

The data of excess pore water pressure at four monitoring points is shown in Fig. 5. There are three times' accumulation and dissipation of pore water pressure occurred during gas injected (0–300 s, 600–1 000 s, 1 300–1 700 s). A transverse crack occurs after the first pressure dissipating, and then a diagonally upward crack occurs after the second pressure dissipating. Finally, gasbag develops to the largest volume in 1 300 s, and the third pressure dissipation is accompanied by the release of gas.

The same changing trend can be found in the pore pressure curve at different positions, with different change range. The pressure at the coarse-fine sediments interface (P_1) occurs the largest range of change, and the value of pore water pressure shows a negative correlation with the distance from the gas source. The shallower the monitoring point being located, the

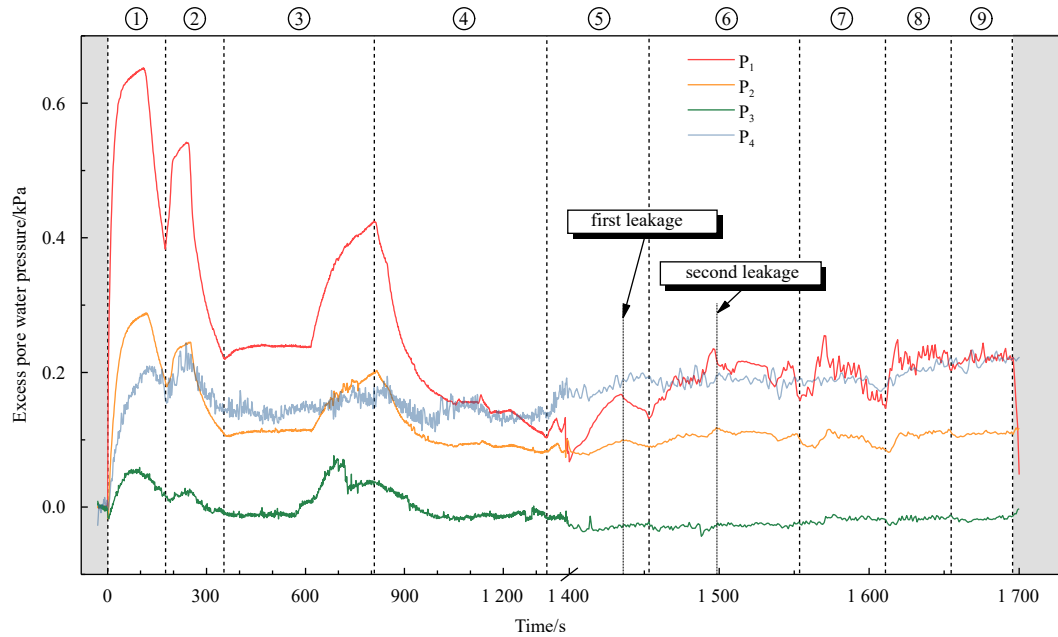


Fig. 5. Changes of excess pore water pressure. The gray section represents the period of no gas injection, and the white section represents the period of gas injection. The circled numbers above indicate the stages of gasbag development: ①transverse crack generation, ②transverse cracks development, ③gasbag expansion longitudinally, ④diagonally upward crack generation, ⑤the first gas release, ⑥the second gas release, ⑦the third gas release, ⑧the fourth gas release, ⑨the fifth gas release.

smaller the range of data change. We selected 80 data points during 0–300 s after gas injected from four monitoring points. the X-axis stands for the distance from the gas source, and the pore water pressure value is exceeded. The different ratio between the extreme value and the distance from the gas source is drawn on the double ordinate in Fig. 6.

In the formation background of this article, the vertical distance between the farthest monitoring point and the gas source is 320 mm (P_4), and the variation range of excess pore water pressure is 0.176 Pa/mm. Combined with Fig. 5, it can be seen that the data of P_4 can represent the pressure change trends since the waveform is relatively simple during the development process of

cracks and gasbag, but it is difficult to judge the gas release process for unobviously data change. The factors affecting the pore water pressure value include gas pressure inside the gasbag (unknown), gas input pressure (10 kPa), cracks, and distance between the gas source and the monitoring locations. During the formation of cracks and gasbag, the pressure of P_3 with the closest distance to the gasbag gradually exceeds the pressure of P_2 with the same vertical height. This phenomenon reflects the influence of the gasbag on the excess pore water pressure. However, there is not research providing data about the internal pressure of gasbag. Thus, it is difficult to quantitatively analyze the influence of the internal pressure of gasbag on the excess

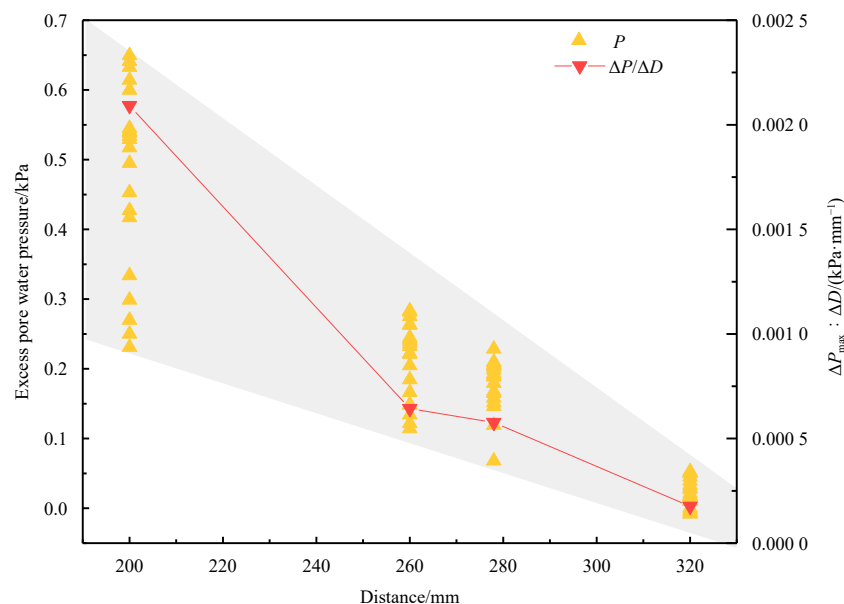


Fig. 6. Relationship between excess pore water pressure (P) and distance (D) from gas source.

pore pressure. Actually, the location deployment of monitoring points is very important, in theory, the closer the monitoring point be located to the damaged area, the greater the pressure changing range, infer the more obvious the change characteristics, and the more able to judge the damage process.

The following section describes the characteristics of the excess pore water pressure and its changing mechanism according to the gasbag development as time goes.

3.2 Corresponding changes of gas pressure in cracks and excess pore water pressure of surrounding medium

At the beginning of gas injection, gas occupies the pore space in coarse-grained sediments to produce fluid expansion. But due to the poor permeability of overlying fine-grained sediments, the drainage of coarse-grained sediments would be blocked, and then excess pore water pressure is rapidly generated which resist gas volume increase. As excess pore gas (water) pressure continues to increase, split cracks are formed in sediments (Zhang et al., 2015a; Campbell et al., 2017), excess pore water pressure dissipates quickly. In this stage, the pressure dissipation curve and dissipation rate do not accord with the natural dissipation law of excess pore water pressure in the consolidation and drainage process. Meanwhile, gas can not escape from the overlying fine-

grained sediments, which all prove that only the forming of cracks can cause the rapid dissipation of pore water pressure. Therefore, it can be infer that the first dissipation of pore water pressure is based on the forming of cracks.

When the cracks form, what characteristic could be seen in the changing of pore water pressure. And what's the relationship between these characteristics and the the changing of gas pressure in cracks? According to the ideal gas equation of state:

$$P_g V_g = nRT, \quad (16)$$

in which, n is mole number, V_g is gas volume, and P_g is gas pressure. In this paper, nRT can be considered as a constant.

The pore gas pressure can also be calculated by the pore water pressure and capillary force P_c :

$$P_g = P_w + P_c. \quad (17)$$

According to Eqs (16) and (17), once the crack forms, the gas pressure and pore water pressure all decrease rapidly with the increasing volume of gas in cracks. We perform a more meticulous calculation based on the analysis. We used software Matlab to

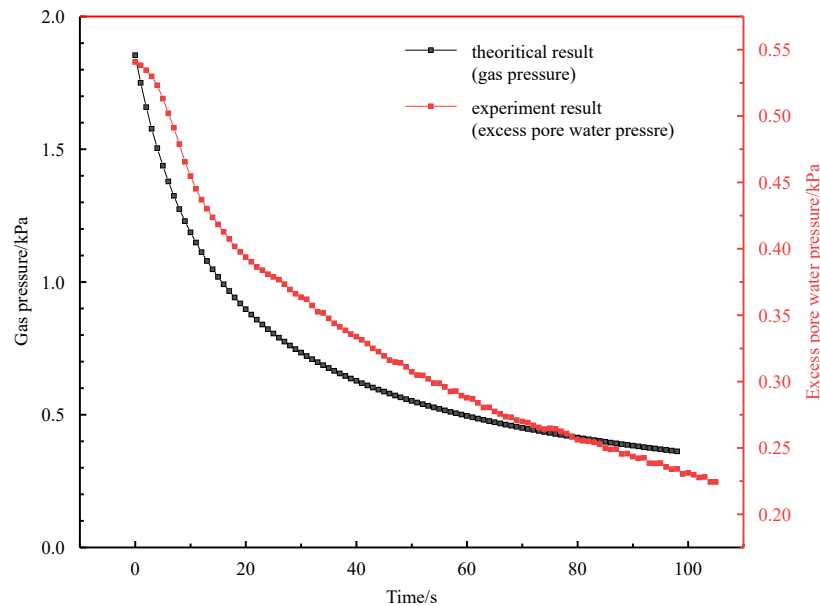


Fig. 7. Comparison of gas pressure in the crack (theoretical) and excess pore water pressure of surrounding medium (experiment).

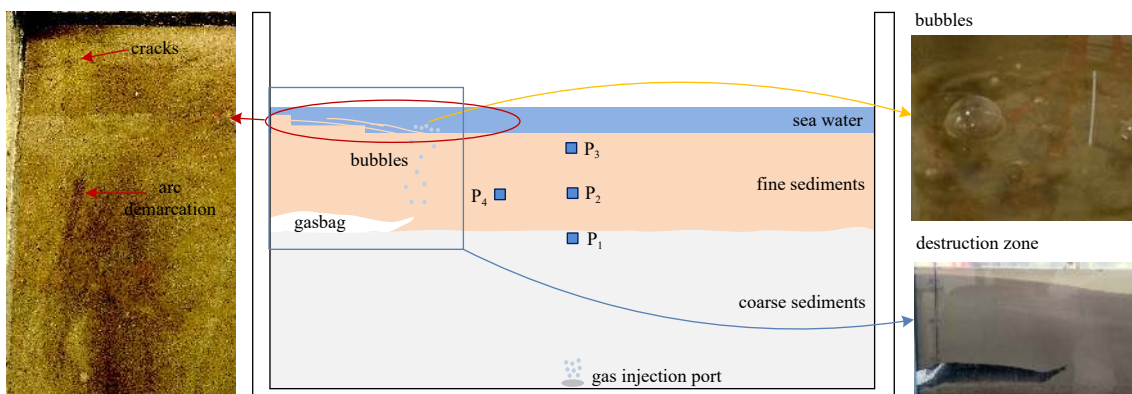


Fig. 8. Damage simulation diagram.

construct a one-dimensional model of gas pressure in the crack (Section 2.4) based on the soil parameters of our experiment. Meanwhile, the comparison between excess pore water pressure (P_e) during 245–349 s and the theoretical gas pressure is shown in Fig. 7.

It can be seen from Fig. 8 that gas pressure in the crack decreases very quickly within 20 s, and then the decreasing rate gradually slows. The change trends of excess pore water pressure and gas pressure are similar. The difference between the theoretical gas pressure and experimental pore water pressure is that the decreasing rate of excess pore water pressure is nearly constant, while the decreasing rate of gas pressure gradually slows in the late stage (80–100 s). The reason for the difference may be due to the fact that the formation of crack changes the stiffness and properties of surrounding sediments, and then causing the capillary force P_c can not still remain constant. Although there exist differences in details, the overall view is consistent, so the formation of cracks in sediments can be judged based on the rapid attenuation of excess pore water pressure.

3.3 Pore water pressure characteristics of gasbag formation

Ascending bubbles encounter a sediments “belt” with lower fracture toughness, the bubbles begin to move laterally and gather below the low fracture toughness area (Boudreau et al., 2005; Boudreau, 2012; Kaminski et al., 2020), which shows a essence that gas encounters a permeation barrier formed by layered sediments with varying particle sizes. The gasbags can easily grow and develop in this stratum environment where the size of sediments decreases from bottom to top.

On the whole, in the formation and development stage of gasbag, excess pore water pressure experiences a double peak accumulation and dissipation and then stabilizes. It can be observed in experiment that formation of the gasbag always begin with formation of the transverse crack. After the length of transverse crack reaches about 180 mm, the crack start to grow longitudinally, forming a gasbag and uplifting the upper fine-grained sediments. The gasbag expands in an irregular triangular pyramid shape, and the value of excess pore water pressure is almost unchanged during the vertical expansion of gasbag (350–600 s). As shown in Fig. 8, the sediments above gasbag are arched and the displacement distance is uneven, so that cracks appear on the surface of fine-grained sediments. The number of cracks increases with the increase of gasbag volume, and a visible arc-shaped boundary (weak sliding area) is developed. Excess pore water pressure accumulates and dissipates again (600–1 000 s) after the growth of gasbag reaching a certain stage, a diagonally upward crack is observed in the sidewall, and then the gasbag volume grows to the maximum (length about 205 mm, height about 30 mm). Finally, the gas begins to release (1 300–1 700 s). Bubbles escape at the arc-shaped boundary area, which corresponding to the gradually closing gasbag.

According to observation in the experimentation and its corresponding changes in excess pore water pressure, the gasbag formation process before gas dissipates can be divided into three stages:

(1) In the initial stage of gasbag formation, the gas volume in sediments is too small to deform the sediments. During this period, the transverse crack sustained growth and expansion. The sediments offset the increased gas pressure and keep the gas volume small by increasing excess pore water pressure before the formation of crack. Once the crack forms, gas pressure and excess pore water pressure show a rapidly reduced trend. The double-peak accumulation and dissipation of excess pore water pressure here indicate that there may exist more than one crack, or the crack can not maintain growth at a certain stage, which

causing the excess pore water pressure to sustained accumulate until the crack could grow again.

(2) In the late stage of gasbag growth, excess pore water pressure cannot increase indefinitely because the retention of excess pore water pressure depends on the permeability and compressibility of sediments (Zhang et al., 2013). As gas volume increasing, sediments will be extruded and then deformed to accommodate gas (Barry et al., 2012), meanwhile excess pore water pressure minor changes because of the uplift of the overlying sediments. During this stage, the crack almost stop growing horizontally, and the growth of gasbag is mainly vertical expansion, experimental data shows that the pressure change is quite small in such gas migration mode of cavity expansion (Johnson et al., 2002; Sun and Santamarina, 2019).

(3) The deformation of sediments caused by gasbag leads to the inhomogeneity of fine sediments layers. At the end of gasbag development, oblique cracks are created, which corresponds to the accumulation and dissipation of excess pore pressure. Finally, a diagonally upward crack develops to the surface of sediments and then causes gas to release.

3.4 The characteristics of excess pore water pressure during intermittent gas release

During gas release stage, excess pore water pressure fluctuates in a zigzag shape, the fluctuation with small absolute value but high frequency shows a slowly increasing trend. There are five rises and falls of excess pore water pressure (Fig. 5), each one corresponds to a gas release process. Some experiments (Acharya et al., 2016; Rocco et al., 2017; Sun and Santamarina, 2019) record pressure changes in the process of gas migration in the soil, it turns out that the pressure change is characterized by a zigzag cycle in which the pressure accumulates to a peak and then drops sharply. It also verifies that the accumulation of gas in sediments can lead to pressure accumulation and the release of gas can lead to a rapid drop in pressure.

There still exist differences in the zigzag-like rise and fall of pressure. According to the research data of this paper, Acharya et al. (2016) and Sun and Santamarina et al. (2019), the extremely low and extremely high values of pressure accumulation in each gas release process are plotted in Fig. 9 (using n to represent the gas release sequence, $n=1, 2, 3, 4, 5$), and data processing includes: obtaining the accumulated pressure ΔP_n by subtracting the extremely high value from the extremely low value of each gas release process, and then normalizing ΔP_n by using $\Delta P_n/\Delta P_1$ to characterize the pressure accumulation of gas release. In the same way, pressurization time Δt_n , doing a similarly process (Fig. 9).

In Sun's experiment, the pressure accumulation value and pressurization time are continuously reduced as gas releasing sequences advance; while in the experiment of this paper and Acharya et al. (2016), the pressure accumulation value and the time of pressurization increase both show volatility. The former one shows the gas escaping position is the same in experimental images. Once the initial gas releasing channel is generated, the porosity of gas release channel will change (Sun and Santamarina, 2019), which means that the damage caused by cracks to fine sediments is permanent. Therefore, the next damage is more likely to occur in the same area after gas breaking through the overlying sediments once. The continuous gas injection can reopen the previous gas release channel at a lower pressure than before one, pressurization time is also shorter. The gas releasing positions do not coincide in this paper, the monitoring research carried out by Acharya *in-situ* has different gas release positions either, which shows the instability and non-uniqueness of gas re-

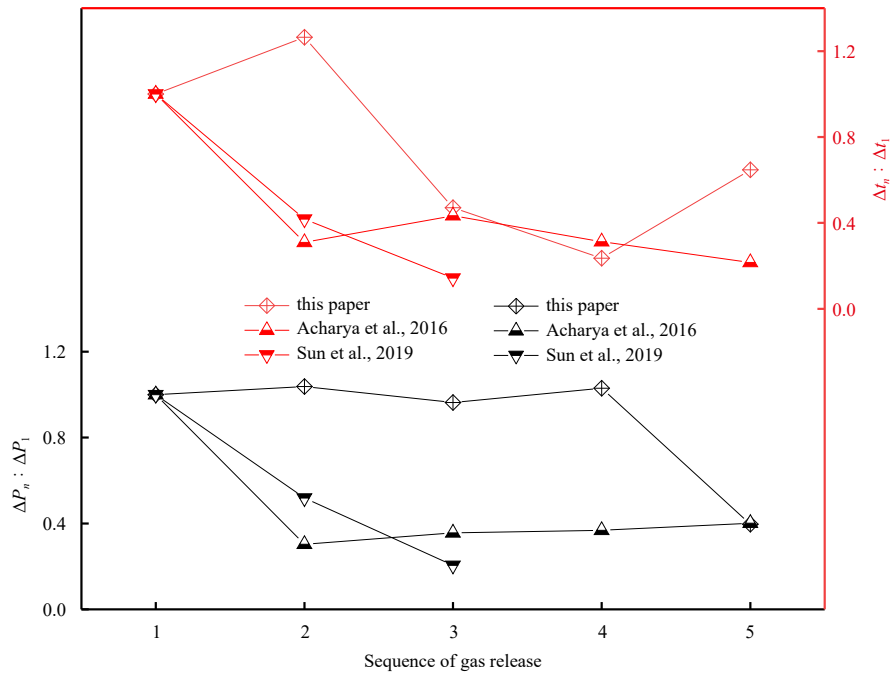


Fig. 9. The pressure and pressurization time trend of different gas release sequences.

lease channels in sediments. So that the pressure accumulation values and pressurization time are random.

Whether gas release channels are changed or no all has an impact on the change characteristics of the pressure waveform. Whether the leakage point is single or multiple can be judge through the changing trend of pressure accumulation values and the time for pressurization, which provides help for data interpretation work of *in-situ* monitoring.

Furthermore, the intermittent release of gas may be converted into continuous release at a certain stage. Whether the gas release is intermittent or continuous depends on the gas injection rate (determining the gas re-pressurization time), sediments properties, and stress condition (determining crack healing time) (Liu et al., 2020). Under some stress conditions, the intermittent gas release is more advantageous, which is related to the opening or closing of gas channels. The pressure drops sharply as gas being released, and then resulting in a decrease in channel diameter. However, when gas injection rate increases or the multiple opening and closing of channels changes the nature of sediments and prolongs the healing time of cracks, the gas is likely to be released continuously.

4 Conclusions

This paper simulates the development process of gasbag at the boundary of coarse-fine sediments layers through model test and monitors by means of pore water pressure. Excess pore water pressure data reflects some typical characteristics and mechanisms of pressure changes during the stages of crack generation, gasbag formation and gas release.

(1) Both theoretical gas pressure and experimental excess pore pressure data show that the pressure value decreases rapidly during crack generation. The pressure value is decreased rapidly by about 50% in the first 20 s under the experimental conditions of this article. Then the decreased rate of pressure data slows gradually. On the whole, there is a good corresponding relationship between excess pore water pressure in sediments and gas pressure in the crack, so the formation of the crack can be

distinguished according to the attenuation characteristics of the excess pore water pressure.

(2) The process of gasbag formation can be divided into three stages: the initial, late and final. In this experiment, generation of gasbag begins with the formation of transverse crack when the pressure accumulates and dissipates for once or twice. Then the crack begins to grow longitudinally which called cavity expansion, and excess pore water pressure tends to be basically unchanged. Oblique cracks occur at the final stage of gasbag development, and excess pore water pressure accumulates and dissipates again.

(3) The oblique crack develops until the gas escapes from the sediment surface, and the variation curve of excess pore water pressure in the gas release stage shows the characteristic of saw-tooth fluctuation. The increase of excess pore water pressure corresponds to gas accumulation and the increase of gas pressure in sediments, while the decrease of excess pore water pressure corresponds to gas release in this experiment.

(4) The pressure accumulation value and the time required for pressure growth in the gas release stage also show fluctuation, indicating the gas pathway in sediments is unstable and not unique, multiple migration channels are developed in the fine sediments, and the numerical change of the pressurization process is random.

(5) The value of excess pore water pressure in sediments is negatively correlated with the vertical distance between sensors and gas source. The excess pore water pressure is closed to linear attenuation with the increasing of vertical distance from gas source, and the farther the sensor is from gas source, the smaller the variation range of excess pore water pressure.

(6) According to the above-mentioned pressure change characteristics, we can apply these to *in-situ* monitoring of gas-induced domes disasters. When excess pore water pressure rises to an extremely high value and then quickly decays, it is likely to be caused by cracks creating in sediments. When excess pore water pressure remains between the extreme values (high and low), it is likely to be a signal that the gasbag begins to expand longitudinally. When

excess pore water pressure has frequent zigzag fluctuations, it is important evidence for the releasing of gas. Based on this signal, the pressure increase value and pressurization time can be further analyzed to determine whether the gas migration channel changes, that means, whether the gas release position is single.

Of course, the interpretation of pore water pressure has multiple interpretation problems. We cannot make absolute judgments on the change characteristics of pore water pressure, but data interpretation can be simplified when specific disaster monitoring is targeted.

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Appendix:

In the initial stage of gas injection, gas in the pipe can be regarded as an ideal fluid for steady flow. For the steady flow of ideal fluid, Smith (1972) proposed that:

$$P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 = P_2 + \frac{\rho v_2^2}{2} + \rho g h_2, \quad (A1)$$

where P represents gas pressure, ρ represents gas density, v represents the velocity of flow, h represents the height of pipeline, and g is the acceleration of gravity. Since the height of both sides of pipes is approximately the same, and under standard atmospheric pressure, the change of gas density caused by P_1 and P_2 can be neglected Eq. (1) is simplified to:

$$P_1 + \frac{\rho v_1^2}{2} = P_2 + \frac{\rho v_2^2}{2}. \quad (A2)$$

The flow of gas in the pipe is the same at any time.

$$v_1 S_1 = v_2 S_2, \quad (A3)$$

in which, S is the cross section area of gas injection pipe, $S_1 = S_2$. Meanwhile, the equation about velocity of flow v and flow Q could be written as follows:

$$Q = vS. \quad (A4)$$

Gas density can be obtained by the following formula:

$$p = \rho RT, \quad (A5)$$

where p represents absolute gas pressure. P_2 is 11.2 kPa according to the Eqs (A2)–(A5). The position of gas injection is 370 mm below water surface where hydrostatic pressure u_0 is 3.7 kPa.

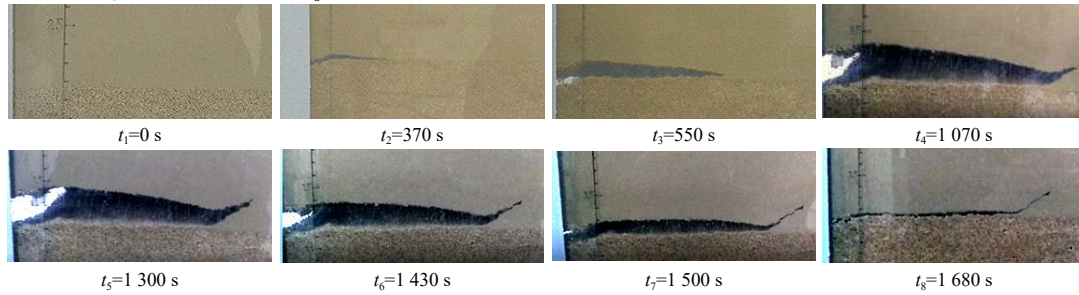


Fig. A1. Experimental photos of gasbag development process.

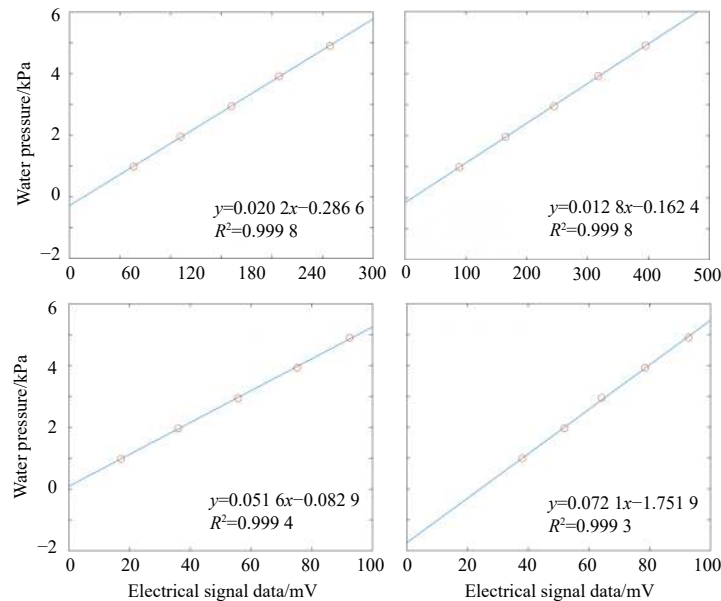


Fig. A2. The calibration formulas of pore water pressure sensors.