Impacts of hydrate on the lateral stress in sediments

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Abstract. The ratio between the horizontal and the vertical effective stresses is defined as the coefficient of earth pressure at rest K_0 . K_0 in hydrate-bearing sediments is critical in understanding the stress states in hydrate-bearing sediments, yet has not been previously understood. An oedometer cell equipped with vertical and horizontal stress measurement sensors is used to measure the evolution of K_0 in tetrahydrofuran hydrate-bearing sands during hydrate formation and dissociation and vertical stress changes. The results show that the response of K_0 in hydrate-bearing specimens reflects the combined effects of hydrate cementation, the viscous nature of hydrate crystals, and the stress levels. These results can enhance the understanding of stress anisotropy and geomechanical behaviors of hydrate reservoirs during gas production.

1 Introduction

The coefficient of earth pressure at rest K_0 indicates the in situ stress state in deposits, and can be defined as the ratio of vertical and horizontal effective stress, as expressed below,

$$K_o = \frac{\sigma'_h}{\sigma'_v} \tag{1}$$

where σ'_{ν} and σ'_{h} are the vertical and horizontal effective stresses. The value of K_{o} in soils can be influenced by many factors, including the effective stress, stress history, the over-consolidation ratio, cementation bonding and debonding, packing density, and particle shape and size [1-5].

For non-cemented soils, the values of K_o does not change significantly during loading, i.e., the lateral stress increases linearly with the increase in vertical stress [2, 3]. The response of the K_o of cemented soils is different from that of the non-cemented soils. For cemented soils, the K_o is mainly governed by the cementation among particles during loading, leading to lower K_o values at low strain conditions [2, 6].

The hydrate crystals in pore spaces can play an essential role in the stress-strain relation, strength, stiffness, permeability, and volume changes of hydratebearing specimens [7-10]. Especially, the increased effective stress caused by the depressurization method for gas production in deep-sea hydrate deposits can induce significant changes in the K_o of hydrate-bearing sediments. Therefore, it is essential to understand the affecting factors of the values of K_o in hydrate-bearing sediments.

The objective of this experimental study is to investigate the evolution of K_o in tetrahydrofuran (THF) hydrate-bearing specimens and to understand the effects

of hydrate crystals on the stress state under zero lateral strain condition.

2 Experimental setup

Fig.1 shows a schematic drawing of a thick-wall oedometer cell (refer to [11, 12] for more details of this setup). The vertical stress is controlled the hydraulic pump in a reaction frame, and a diaphragm pressure transducer installed at the middle height of the specimen monitors the lateral stress response. Porous bronze disks are embedded on the pedestals to allow uniform drainage of the pore fluid throughout the test. The whole experimental setup is placed into a freezer to control the experimental temperature with an accuracy of 0.1°C.

F110 fine quartz sands (maximum void ratio $e_{max} = 0.85$, minimum void ratio $e_{min} = 0.54$, mean particle size $d_{50} = 120 \mu$ m, and uniformity coefficient $C_u = 1.21$) are used in this experimental study. The specimens have a diameter of 50.8 mm, and a height of 30.5 mm with the relative packing density $D_r = 40\%$ and the corresponding void ratio e = 0.726. The ratio of specimen height and diameter (H/D) is limited to 0.6 to prevent the boundary effects from the top and bottom pedestals [13]. The F110 sands are mixed with a predetermined ratio of THF and deionized water. The mass ratio of THF and deionized water is 0:100 for $S_h = 0$ (water-saturated) and 20.3:79.7 for $S_h = 0.96$ specimens.

After packing, the specimen temperature is lowered to 0.1°C to trigger hydrate formation. During the hydrate formation, 25 kPa vertical stress, caused by the self-weight of the top pedestals, is applied to the specimens. Once a thermal peak indicating the initiation of hydrate nucleation is observed, the temperature is kept constant for at least additional 24 hours. Meanwhile, the vertical

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displacement, lateral stress, and P-wave velocity are continually monitored to confirm the completion of hydrate formation. After hydrate formation, additional vertical stress is applied stepwise to the specimens up to 25 MPa. Each loading step is applied at a rate of approximately 5 MPa per minute until the targeted vertical stress is achieved and then held constant. The lateral stress is measured throughout the hydrate formation and the loading processes.



Fig. 1. A schematic drawing of the instrumented oedometer cell for lateral stress measurement.

3 Experimental results

Fig.2 shows the time-lapse temperature, horizontal stress, and calculated K_o during hydrate formation in the $S_h = 0.96$ sediment. The initiation of hydrate crystallization is indicted by the thermal spike. No vertical deformation is observed during hydrate formation. However, the lateral stress increases from approximately 15kPa up to about 35kPa and gradually decreases, under a constant vertical stress of 25 kPa. Thus, the calculated K_o shows the same time-lapse trend.



Fig. 2. Evolution of temperature, horizontal stress, and K_0 during hydrate formation.

Fig.3 presents the evolution of vertical and lateral stresses and the corresponding K_o response with elapsed time during the stepwise loading. The $S_h = 0$ sediment shows a slight decrease in K_0 at the moment of each loading step and then stabilizes in minutes. For the $S_h = 0.96$ sediment, the temporary reduction followed by a gradual increase in K_o is observed during each loading step.



Fig. 3. Experimental results of the time-lapse vertical and horizontal stresses in the tested specimens. (a) $S_h = 0$ (water-saturated) sediment. (b) $S_h = 0.96$ (hydrate-bearing) sediment.

4 Discussion

The response of K_o during loading is summarized in Fig. 4. For $S_h = 0$ (water-saturated) specimen, K_o slightly decreases with increasing vertical stress. The minor reduction in K_o indicates a stiffer specimen, attributed to the compaction effects by the increased vertical stress.



Fig. 4. Changes in the coefficient of earth pressure at rest K_{θ} of $S_h = 0$ (black circle markers) and 0.96 (green cross markers) specimens during loading. The loading process starts from 0.025 MPa and up to 25 MPa.

The hydrate-bearing sediments $S_h = 0.96$ show a significant reduction of K_0 at the low vertical stress level ($\sigma_v < 1$ MPa). A lower K_o value indicates a less pronounced stress transfer from the vertical to the lateral direction. With further increase of vertical stress, the K_o

firstly decreases at the moment of vertical loading and then rises under a constant vertical load, indicating a viscous behavior in stress transfer. Since no such evident time-lapse behavior is detected in the $S_h = 0$ specimen, it can be concluded that the presence of hydrate crystals causes such a creep behavior in the K_o of the hydratebearing specimen. Since quarzitic sands do not present significant creep behaviors [14], the observed apparent time-delayed response of stress transfer in hydratebearing sediments highlights the critical role of hydrate crystals in the stress state of hydrate-bearing sediments.

The hydrate crystals can enhance the strength and the stiffness of hydrate-bearing specimens [15-17]. The reduction of K_o for the $S_h = 0.96$ specimen under relatively low vertical stress ($\sigma_v < 1$ MPa) is primarily caused by the cementation between soil particles and hydrate crystals. The cementation supports and shares the applied verticals stress and causes less pronounced lateral stress transfer [2, 4, 7]. Also, hydrate crystals can act as part of the skeletal structure that carries the load together with soil particles [16]. At relatively high vertical stress (1 MPa < $\sigma_v < 25$ MPa), the K_o of the hydrate-bearing specimen is mainly governed by the sand skeleton after losing the majority of cementation.

Conclusions

This study experimentally examines the evolution of the coefficient of earth pressure at rest K_o in hydratebearing specimens. The main findings follow.

- The K_0 of the hydrate-free specimen ($S_h = 0$, watersaturated) decreases slightly from 0.63 to 0.51 as the vertical stress increases from 25 kPa to 25 MPa, mainly due to the compaction effect that stiffens the specimen.
- The hydrate-bearing specimen $(S_h = 0.96)$ shows a significant reduction in K_o , reflecting the role of hydrate crystals in bonding the sand particles and thus less stress transfer in the horizontal direction.
- The presence of hydrate crystals plays a vital role in the viscous response of *K*_o during loading.
- With further increases in the vertical stress, the *K*_o value increases, mainly governed by the sand skeleton after the debonding of hydrate cementation.

The work is supported by the DOE/NETL gas hydrate research program.

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