Local hydraulic resistance of compacted sand-bentonite mixture

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Abstract

The paper aimed to assess the resistance to hydraulic fracture/water-inducing internal erosion in compacted sand-bentonite mixtures. Water was injected into a ϕ-10 cm × 10 cm compacted sample through the starter slots. Two types of starter slots were used, which led the water pressure to be locally distributed in vertical or horizontal directions. Local hydraulic pressure resistance of compacted mixtures was determined through measurement of flow rates. Test results indicated the existence of a pressure level called herein breakthrough pressure above which sudden increase in flow rate was observed. The overburden stress, density and bentonite content were found to strongly affect the breakthrough level. It was found that hydraulic fracture was first initiated when water pressure attained this critical level. Subsequently internal erosion may or may not occur. Sample with small bentonite content exhibited smaller fracture zone and large amount of erosion was observed. In the contrary, total splitting (fracture) of sample was observed in mixture with higher bentonite content. The linear relationships between the normalized breakthrough pressure (ratio between breakthrough pressure to the undrained shear strength) and the normalized undrained shear strength were observed for all cases.

1. Introduction

Sand-bentonite mixtures, due to their low hydraulic conductivity, have been widely used as hydraulic barriers, especially in places where availability of clay is limited. Long term functioning of the material; i.e., water tightness, is therefore the prime concern. In clayey soil, application of high fluid pressure may result in hydraulic fracture. Theoretically, the orientation of hydraulic fracture depends upon the direction of the applied fluid. The water pressures required to induce fractures, $(P_w)_H$ or $(P_w)_V$, can be written as (Valko and Economicles, 1995 and Anderson et al. 1994):

$$(P_w)_H = \sigma_v' + t_v : \qquad (1a)$$

In case where fracture is horizontally induced

$$(P_w)_V = \sigma_h' + t_h : \qquad (1b)$$

In case where fracture is vertically induced

Where σ_v', t_v and σ_h', t_h are the effective stresses and tensile resistances in the vertical and horizontal directions, respectively. In nature, fracture usually occurs in parallel to the vertical plane, which is perpendicular to the direction of the minor principal stress component (Massarsch, 1978, Jaworski et al.1981, Overy and Dean, 1986 and Anderson et al. 1994).

In sand-clay mixture, detachment of fine particle may also occur. In mixture with lower hydraulic conductivity, initiation of fracture may result in subsequent erosion along the surface of fracture plane. Deterioration of long term hydraulic resistance of a sand-clay mixture is hence caused by either formation of hydraulic fracture or internal erosion.

In the present study, an experimental program was arranged to examine the local hydraulic resistance of the sand-bentonite mixtures. The influences of a few physical factors; i.e., bentonite content, overburden stress, orientation of water pressure and rate of pressure application, were investigated.

2. Experimental program

Sand collected from the Singh River in the central part of Thailand was used. It has an average diameter, D_{50}, and coefficient of niformity, U_c, of about 0.6 mm and 4.0, respectively. It naturally contained about 0.6% of fines content (smaller than 75 μm) which was excluded before mixing with the bentonite powder. The commercially available Montmorillonite from Rayong Province, Thailand, called Mac Gel was used. The specific gravity and moisture content (air-dried) of this bentonite were 2.5 – 2.7 and 8 – 10%, respectively.

Dry sand and air-dried bentonite powder were thoroughly mixed before distilled water was added. Mixing was continued until a uniform mixture with about 18% water content was obtained. Mixture was left in a humidity-controlled chamber for 24 hour before compacted following the Standard Proctor to form a 10-cm diameter cylinder sample. After application of the overburden stress, de-aired water was allowed to flow through the sample. Vertical displacement was used to indicate the completion of consolidation, which usually took about 48 hours. Table 1 summarizes the general testing conditions of the mixtures used.

Test was started by locally applying water pressure through the starter slot installed at the center of the chamber (Fig.1). Two types of starter slots; i.e., vertical and horizontal slots, were used as shown. Tests were conducted in two manners as briefly describing herein..

(a) *Slow test*: In this test, water pressure was increased by increments of 10 kPa and was kept constant for about 180 minutes during which flow rate was measured.

(b) *Quick test*: In this test, water pressure was increased by increments of 10 kPa and held for about 1 minute for measurement of flow rate.

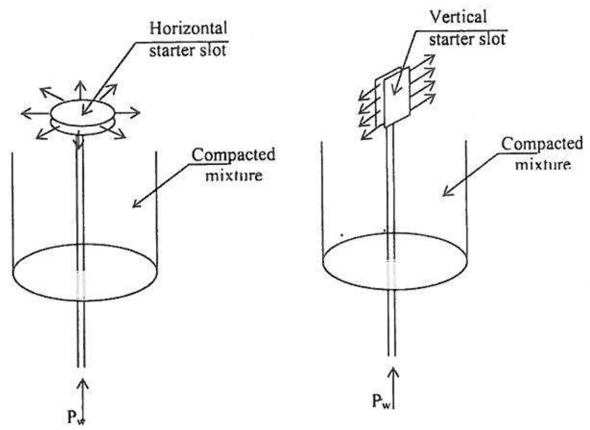


Fig. 1 Test arrangement for vertical and horizontal hydraulic resistances

3. Test results and discussion

Fig.2(a) and 2(b) shows the typical test relationships between the applied water pressure and flow rate obtained from quick and slow testes conducted under overburden stress of 100 kPa, respectively. It should be noted that flow rate was computed from the amount of water flowing into the starter slot. For all tested cases, when water pressure exceeds a certain level, sudden increase in flow rate can be clearly seen. This pressure level is called herein the breakthrough pressure. It is believed that fractures and/or initial seepage paths were initiated at this pressure level.

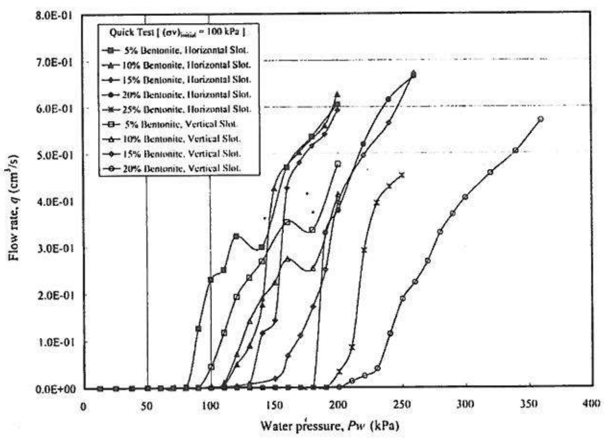


Fig. 2(a) Relations of flow rate and water pressure of quick test under overburden pressure = 100 kPa.

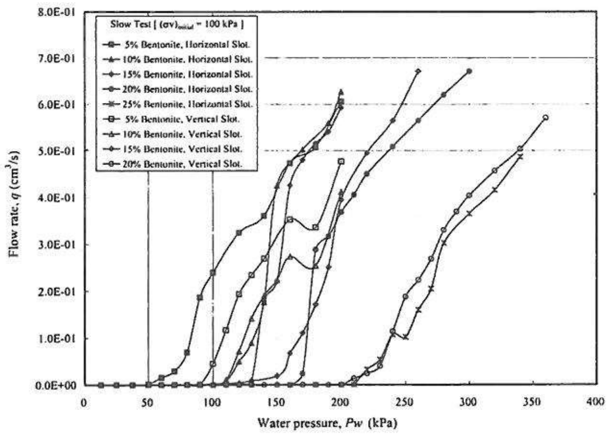
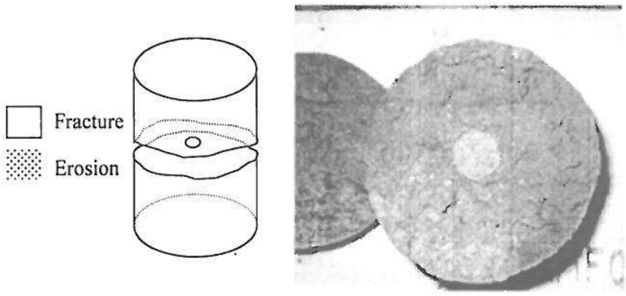


Fig. 2(b) Relations of flow rate and water pressure of slow test under overburden pressure = 100 kPa.

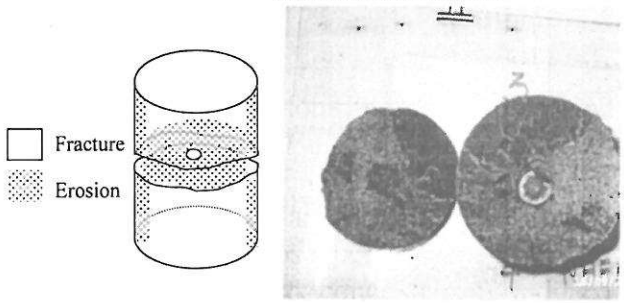
The measured breakthrough pressures obtained from samples using horizontal and vertical slots are almost similar. This is because the boundary condition imposed from the equipment. In the current set up, tested sample is allowed to freely move up/down to maintain condition of constant overburden stress. In the other hand, due to its cylindrical nature, the circumferential stress is not constant. It increases almost equally to the amount of the applied water pressure. Under high water pressure (but still lower than the breakthrough level), the overburden stress becomes the least stress and horizontal plane is the most susceptible to fracture. As a consequence, similar breakthrough pressure was obtained from tests conducted using horizontal and vertical slots. The observed fractures plane (details being discussed in the next paragraph) from samples tested using the vertical starter slot were mostly inclined close to horizontal plane.

By visual inspection of the tested specimens, a few main patterns of fracture and/or erosion can be categorized (Fig. 3). These patterns of fracture/erosion observed from each test are shown in Table 1. The following remarks can be drawn.

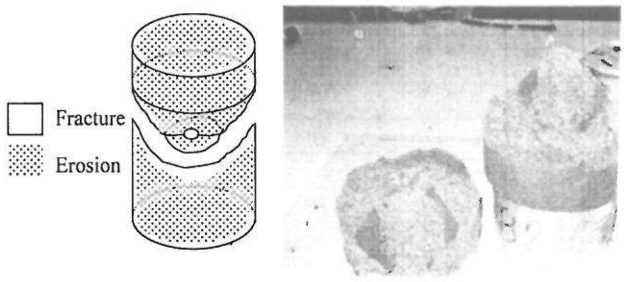
(a) Tests conducted using horizontal slot.
Sample with high amount of bentonite content (≥ 15%) was clearly split along the horizontal plane (*HF*). Erosion along the horizontal plane was also observed (*HF-E1*) for some cases. In sample with less bentonite content, initial horizontal fracture was formed in a limited extent and the subsequent seepage paths (upward or downward cone shapes) induced severe erosion (*HF-E2*).



HF : Full splitting of sample along horizontal plane. Almost no trace of erosion



HF-E1 : Splitting of sample along horizontal plane. Erosion is observed



HF-E2 : Splitting of sample is flat near starter slot and c either up or down.Erosion is clearly observed

Fig.3(a) Patterns of fracture/erosion observed from tests using horizontal slot

(b) Tests conducted using vertical slot.
There was no clear vertical fracture plane found in the tests. In sample with 20% bentonite content, erosion along the lead pipe of the starter slot was found (*VE*). This is because (1) vertical fracture cannot be formed (as reason given in the previous paragraph), (2)

Table 1(a) Initial testing conditions and fracture patterns (*Slow Test*, Horizontal slot)

Sample No.	Description				Breakthrough Pressure P_b kPa	Fracture Pattern**
	Bentonite Content B %	Water Content w %	Over burden Pressure σ_v kPa	Dry Density γ_d t/m3		
SHF 01	5	18	100	1.48	60	*HF-E2*
SHF 06	5	18	200	1.45	160	*HF-E2*
SHF 11	5	18	300	1.53	210	*HF-E2*
SHF 02	10	18	100	1.32	100	*HF-E2*
SHF 07	10	18	200	1.45	200	*HF-E2*
SHF 12	10	18	300	1.51	240	*HF-E2*
SHF 03	15	18	100	1.34	130	*HF-E1*
SHF 08	15	18	200	1.46	230	*HF*
SHF 13	15	18	300	1.57	300	*HF-E1*
SHF 04	20	18	100	1.32	180	*HF-E1*
SHF 09	20	18	200	1.35	220	*HF-E1*
SHF 14	20	18	300	1.46	340	*HF-E1*
SHF 05	25	18	100	1.33	190	*HF-E1*
SHF 10	25	18	200	1.31	290	*HF*
SHF 15	25	18	300	1.30	360	*HF*

** referred to Fig. 3

Table 1(b) Initial testing conditions and fracture patterns (*Slow Test*, Vertical slot)

Sample No.	Description				Breakthrough Pressure P_b kPa	Fracture Pattern**
	Bentonite Content B %	Water Content w %	Over burden Pressure σ_v kPa	Dry Density γ_d t/m^3		
SVF 01	5	18	100	1.51	90	*OE*
SVF 06	5	18	200	1.48	160	*OE*
SVF 11	5	18	300	1.50	250	*OE*
SVF 02	10	18	100	1.46	100	*IF-E*
SVF 07	10	18	200	1.42	150	-
SVF 12	10	18	300	1.48	280	*IF-E*
SVF 03	15	18	100	1.43	150	*IF-E*
SVF 08	15	18	200	1.48	260	*IF-E*
SVF 13	15	18	300	1.45	300	*VE*
SVF 04	20	18	100	1.43	210	*VE*
SVF 09	20	18	200	1.43	220	-
SVF 14	20	18	300	1.45	330	*VE*

** referred to Fig. 3

Table 1(c) Initial testing conditions and fracture patterns (*Quick Test*, Horizontal slot)

Sample No.	Description				Breakthrough Pressure P_b kPa	Fracture Pattern**
	Bentonite Content B %	Water Content w %	Over burden Pressure σ_v kPa	Dry Density γ_d t/m3		
QHF 01	5	18	100	1.49	80	*HF-E2*
QHF 06	5	18	200	1.48	150	*HF-E2*
QHF 11	5	18	300	1.48	210	*HF-E2*
QHF 02	10	18	100	1.45	100	*HF-E2*
QHF 07	10	18	200	1.47	180	*HF-E2*
QHF 12	10	18	300	1.47	250	*HF-E2*
QHF 03	15	18	100	1.43	130	*HF-E2*
QHF 08	15	18	200	1.43	230	*HF-E2*
QHF 13	15	18	300	1.45	320	*HF-E1*
QHF 04	20	18	100	1.33	180	*HF-E1*
QHF 09	20	18	200	1.35	270	*HF*
QHF 14	20	18	300	1.44	350	*HF*
QHF 05	25	18	100	1.31	190	*HF*
QHF 10	25	18	200	1.31	290	*HF*
QHF 15	25	18	300	1.41	360	*HF*

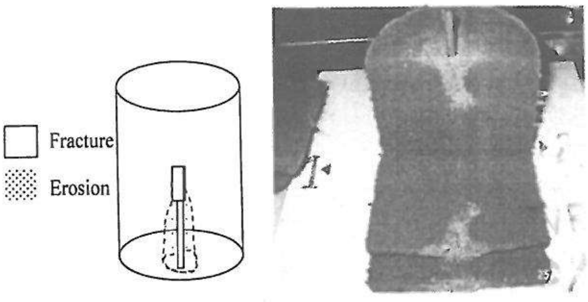
** referred to Fig. 3

Table 1(d) Initial testing conditions and fracture patterns (*Quick Test*, Vertical slot)

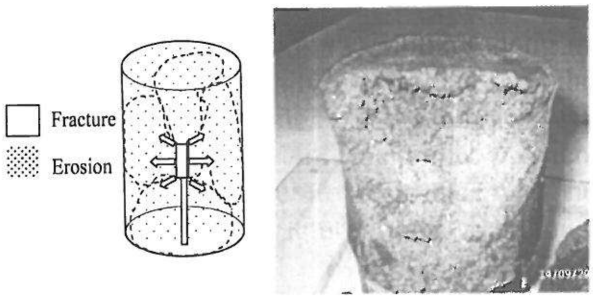
Sample No.	Description				Breakthrough Pressure P_b kPa	Fracture Pattern**
	Bentonite Content B %	Water Content w %	Over burden Pressure σ_v kPa	Dry Density γ_d t/m3		
QVF 01	5	18	100	1.51	90	*OE*
QVF 06	5	18	200	1.50	150	*OE*
QVF 11	5	18	300	1.50	200	*OE*
QVF 02	10	18	100	1.46	110	*OE*
QVF 07	10	18	200	1.46	200	*OE*
QVF 12	10	18	300	1.48	260	*IF-E*
QVF 03	15	18	100	1.43	130	*IF-E*
QVF 08	15	18	200	1.43	210	*VE*
QVF 13	15	18	300	1.45	300	*IF-E*
QVF 04	20	18	100	1.43	170	*VE*
QVF 09	20	18	200	1.40	270	*VE*
QVF 14	20	18	300	1.45	320	*VE*

** referred to Fig. 3

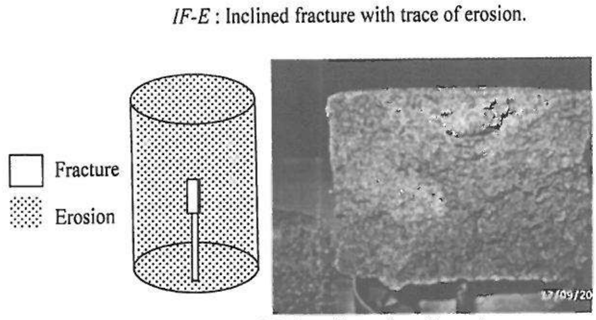
water pressure was not well oriented to form the horizontal fracture plane as those tested using horizontal slot and (3) mixture along the lead pipe may be locally looser than the other parts of the sample. The sample with intermediate amount of bentonite content, whose horizontal fracture resistance was not too high, inclined fracture plane was found together with trace of erosion (*IF-E*). Overall erosion (*OE*) was also observed in sample with small amount of bentonite.



VE : Vertical erosion along the lead pipe of starter slot



IF-E : Inclined fracture with trace of erosion.



OE Overall erosion of sample.

Fig.3(b) Patterns of fracture/erosion observed from tests using vertical slot

The influence of the overburden stress on the breakthrough pressure is summarized in Fig. 4. In general, the breakthrough pressure increases as the overburden stress increases. It should also be noted that the least water pressure required to initiate fracture/erosion is the overburden stress as indicated by Eqn.(1).

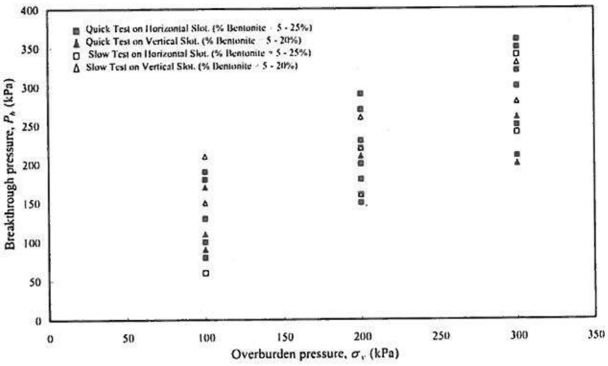


Fig. 4 Relations of breakthrough pressure and overburden stress.

Unconfined compression tests were conducted on samples of similar compacted mixtures. Its variation against bentonite content is plotted in Fig. 5. As can be expected, sample with higher bentonite content exhibits higher undrained shear strength. Since undrained shear strength should have direct relation to the tensile strength (t_h) in Eqn.(1), normalization of breakthrough pressure by the undrained shear strength may provide a useful correlation.

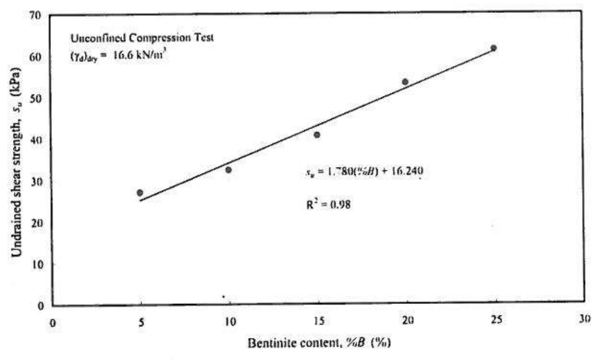


Fig. 5 Variation of undrained shear strength against bentonite content.

Fig. 6 shows the plot between the normalized breakthrough pressure, P_b/s_u, and the normalized overburden stress, σ_v/s_u. The linear and almost unique correlation is obtained from such normalization. Although unconfined compression test does not reflect actual undrained shear strength of the samples with varied overburden stress, the correlation given in Fig. 5 is useful for preliminary estimation of local hydraulic resistance.

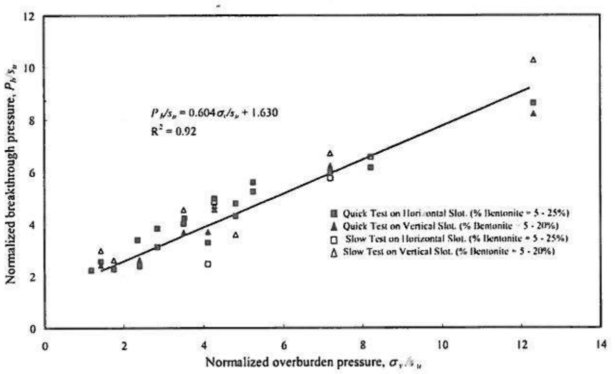


Fig. 6 Relations of normalized breakthrough pressure and overburden stress.

4. Conclusions

A laboratory testing program was established to assess the resistance to hydraulic fracture in the compacted sand-bentonite mixture. It was found that flow rate immediately increased when the applied pressure achieved a certain level. This was called the breakthrough pressure. The minimum pressure required to induce breakthrough was the overburden stress. By visual observation, some extents of fractures were first formed. It could either be fully extended or provided initial seepage paths for subsequent internal erosion.

References

Anderson, K. H., Rawlings, C. G., Lunne, T. A. and By, T. H. 1994. Estimation of hydraulic fracture pressure in clay. Canadian Geotechnical Journal, 31, 817-828

Jaworski, G. W. Duncan, J. M. and Seed, H. B. 1981. Laboratory study of hydraulic fracturing. Journal of the Geotechnical Engineering, ASCE, Vol.107, No.GT6, pp.713-732.

Massarsch, K. R. New aspects of soil fracturing in clay. Journal of the Geotechnical Engineering, ASCE, Vol.104, No.GT8, pp.1109-1121.

Overy, R. F. and Dean, A. R. 1986. Hydraulic fracture testing offshore. Proc. Of the 18th Offshore Technology Conference, Houston, Vol.3, pp.45-53.

Valko, P. and Economicles, M.J. 1995. Hydraulic fracture mechanics. John Wiley & Sons, 298.p.