Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

Experimental Studies on the Bohai Sea Ice Shear Strength

Shun-ying Ji [1] Hong-liang Liu [2] Peng-fei Li [3] Jie Su [4]

Abstract: Shear strength is a basic mechanical property of sea ice, and affects directly the determination of ice loads on offshore structures and the breakup behavior of ice cover in sea ice dynamics. This paper studies the influences of ice temperature, brine volume and shear stress rate on sea ice shear strength using laboratory shear tests with single shear plane and lateral confinement. Ice samples are collected from the Laizhou Bay and the Yellow River Delta of the Bohai Sea. Experimental results show sea ice shear strength increases linearly with decreasing temperature and increasing shear stress rate, and decreases exponentially with the square root of brine volume, respectively. Considering the influences of both brine volume and shear stress rate comprehensively, this paper presents a double-parameter function to determine the sea ice shear strength.

Keywords: sea ice; shear strength; brine volume; shear stress rate; ice temperature

Introduction

Interactions occur between ice floes, and between ice and structures under the influences of ocean currents, waves and tides. Ice constantly breaks up and structures continuously vibrate during the interactions. Sea ice mechanical properties are directly related to the safety of structures in ice-covered regions (Timco and Weeks, 2010; Strub-Klein and Sudom, 2012). With the effect of coastal boundary constraints and sea ice internal forces, sea ice has strong characteristics of break-up, rafting and build-up (Croasdale, 2012). Therefore, the shear strength of sea ice can also be applied to determine the break-up of ice covers in the numerical simulation of sea ice dynamics. Sea ice presents different failure modes including buckling, compression, shear and bending due to its material properties and the diversity of marine structure forms. Shear failure is one of basic failure modes in both nature and the laboratory (Wright and Timco, 2001; Schulson, 2004; Marchenko and Makshtas, 2005). Moreover, it is an important parameter to predict ice loads in engineering practice (Whillans and Merry, 2001; Timco and Weeks, 2010).

It is difficult to realize pure shear in sea ice shear strength experiments, and there are no unified standards to follow internationally (Timco and Weeks, 2010). Shear test methodologies for metals or rocks are often adopted, including single shear, double shear and single shear with lateral confinement (Saeki and Ono, 1985; Repetto-Llamazares et al., 2011). Sea ice is a kind of naturally complex material, and its mechanical characteristics present variability due to changes of environmental factors. Sea ice shear strength is closely related to its crystal structure, temperature and salinity, and the value is commonly in the range of 0.5MPa~2.5MPa. In the early studies, Butkovich (1956) conducted double shear tests with a

---

[1] Professor, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, 116023, China (Corresponding author). E-mail: jisy@dlut.edu.cn.

[2] Graduate student, Department of Engineering Mechanics, Dalian University of Technology, Dalian, 116023, China.

[3] Graduate student, Department of Engineering Mechanics, Dalian University of Technology, Dalian, 116023, China.

[4] Associate Professor, College of Physical and Environmental Oceanography, Ocean University of China, Qingdao, 266003, China.

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

cylindrical specimen and found the average shear strength of first year sea ice was 1.6 MPa in the temperature range of -5 to -7 °C and 2.3 MPa in the range of −10 to −13 °C with a salinity of 6‰. Pounder and Little (1959) carried out single direct shear tests and determined the shear strength ranged from 0.65 to 0.85 MPa for summer ice in the Arctic. Paige and Lee (1967) carried out tests on specimens made from cores of natural sea ice, and obtained strengths in the range of 0.5 to 1.2 MPa with a significant dependence on brine volume. Sea ice shear strengths in planes perpendicular to the ice growth direction are greater than those in planes parallel to the ice growth direction, and generally increase more rapidly with decreasing ice temperature (Saeki and Ono, 1985; Timco and Weeks, 2010). Triaxial compression tests also involve ice shear failure, and the change of loading rate as well as the friction characteristics are crucial for the analysis of the shear failure process (Gupta and Bergstrom, 2002; Fortt and Schulson, 2009).

For the Bohai Sea ice in China, Zhang et al. (1995) analyzed the sea ice shear strength under different ice temperatures and strain rates using the double shear method. Yue et al. (1994) studied the relationship between shear force and lateral force with laterally confined single shear tests. However, the ranges of ice temperature and ice type chosen were not wide enough. Li et al. (2002) then investigated the shear strength considering ice temperature, salinity and strain rate. However, the available sea ice shear strength data are relatively limited, and recently little work has been done on mechanical properties of the Bohai sea ice.

In the winter of 2011-2012, we measured the sea ice physical and mechanical properties comprehensively, and obtained the influence of ice temperature, salinity and loading rate on the compressive strength, flexural strength and shear strength. This paper aims to perform shear strength experiments of the Bohai level ice with laterally confined single shear test, and focus on analyzing the influence of brine volume (temperature and salinity) and shear stress rate on the shear strength.

Experiment Tests of Sea Ice Shear Strength

Sea Ice sample collection

We performed a field survey of sea ice physical and mechanical properties at six different test sites, conducted field measurements, and collected sea ice samples in Laizhou Bay and the Yellow River Delta of the Bohai Sea. Figure 1 shows the sea ice sampling locations, and Table 1 lists the sea ice physical properties. The ice density is determined by the ratio of the mass of ice sample to its volume. The ice sample was melted to measure its salinity with a salinity meter. In table 1, the root of mean square errors (RMSE) of salinity and density are also listed to describe their variation. Sea ice shear strength is affected by many factors, such as ice crystal size and orientation, ice temperature, salinity and loading direction. In order to make sure that the ice samples had similar crystal structure and c-axes orientation, we chose newly formed level ice near the coast as samples, and measured sea ice temperature and salinity cross-section in suit prior to collecting ice samples.

The level sea ice samples were cut into blocks roughly 500mm×700mm in size at the sample collection sites, then sealed in plastic bags and stored in a refrigerating cabinet at -15℃. The rough ice samples were then transported to the laboratory with the refrigerating cabinet. In the laboratory, the ice samples were accurately milled to the required size.

Experimental method

Sea ice has complex material properties with anisotropy in crystal structure and different strengths

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

along different loading directions. Consequently, the consistency of the size and crystal growing direction must be verified during sample preparation. The sample size was 70mm×70mm×50mm, and each was held at a constant temperature for 24 hours to ensure temperature uniformity.

Sea ice has low tensile strength because of its brittle behavior. Small tension forces can lead to obvious experimental error. Therefore, tension should be avoided during tests. Figure 2 (a) and (b) shows the laterally confined single shear device used, which can deal with tension problems to a large extent. Two rigid steel plates of 12mm thickness are designed to supply sufficient lateral confinement with little deformation. To reduce the influence of the confining plates on the shear stress, the interface of the steel plates with the ice sample are smoothed to minimize friction. The main function of the confining plate is to supply a moment to prevent the rotation of the ice sample. Thus, the confining force is not large and is about 100N in the test. If the friction coefficient between ice sample and the confining plates is set to 0.1, the transmitted load from the confining plates is about 10N. Its influence on shear stress can effectively be ignored.

In order to study the influence of temperature and loading rate, samples were placed in the freezer for at least 24 hours at the required temperature, then tested with different loading rates with a low temperature testing machine. During the tests, the sea ice temperature was controlled in the range of -3℃ to -17℃ with a stress rate of 0.03 to 0.18 MPa/s. Loads were applied to the sea ice samples at a constant loading rate and at strictly controlled temperatures until shear failure occurred. The force and displacement of the indenter were recorded automatically. Sea ice temperature and salinity of each sample were immediately measured after the shear test. A small hole was drilled into the ice sample to measure the temperature with a thermometer.

In the shear tests with lateral confinement, the shear plane has a shear are $A = bh$, where b and h are the height and width of the ice sample, respectively. The shear plane can be seen from a broken ice sample after the shear test, shown as Figure 2(c). We assume the shear stress is distributed uniformly in the shear plane and the shear stress can be determined with the ratio of the shear force, F to the shear plane area, A. When shear failure occurs, the ice sample shear stress reaches its maximum value, namely, shear strength σ_s, which can be calculated as,

$$\sigma_{\mathrm{s}} = \frac{F_{\max}}{bh} \tag{1}$$

where $F_{\max}$ is the maximum shear force when the ice sample fails obtained from the measured load-time curve. Figure 3 is a typical shear force-displacement curve under the testing conditions when the ice temperature is -10.8 ℃, salinity is 3.0 ‰ and stress rate is 0.14 MPa/s.

Factors Influencing Sea Ice Shear Strength

Influence of ice temperature

Temperature is one of the two important factors determining sea ice brine volume and has a significant effect on the mechanical properties of sea ice. Experimental results showed that sea ice shear strength increases with decreasing temperature (Saeki and Ono, 1985; Timco and Weeks, 2010). Other research has shown that sea ice shear strength increases with decreasing temperature but upon reaching its maximum value, then shows a decrease in shear strength with further decreases in temperature (Zhang et

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

al., 1995).

Figure 4 plots the sea ice shear strength at different ice temperatures. It shows the shear strength σ_s increases with decreasing temperature and presents an obvious linear trend. The linear relationship between σ_s and temperature T_i can be fitted as:

$$\sigma_s = aT_i + b \tag{2}$$

where T_i is the ice temperature and the two parameters a and b can be determined from the measured data. In Fiture 4, a=-0.076 and b=0.179 with a correlation coefficient of R^2=0.51. The range of the data points in Figure 4 indicate obvious discrete features that influence the shear stress such as stress rate, ice salinity, and ice crystal structure. Stress rate was in the wide range of 0.03MPa/s to 0.19MPa/s for these data points.

Influence of brine volume

For sea ice with high salinity under natural conditions, more brine pockets result in a decrease of sea ice strength. The combined effects of ice temperature, salinity and density have a great influence on sea ice shear strength. The relationship between shear strength and brine volume was also statistically analyzed.

Brine volume is a function of temperature and salinity, and can be determined by (Frankenstein and Garner, 1967)

$$v_b = S_i(0.532 + \frac{49.185}{|T_i|}), \quad -0.5℃ \geq T \geq -22.9℃ \tag{3}$$

where S_i is the ice salinity(‰).

Based on a previous obtained relationship between shear strength and brine volume (Li et al., 2002; Timco and Weeks, 2010), the relation between σ_s and $\sqrt{v_b}$ can be fitted with a power-law function as

$$\sigma_s = \alpha \sqrt{v_b}^{(-\beta)} \tag{4}$$

where the two parameters α and β can be determined from the measured data. Figure 5 shows the fitted curve with α = 0.18 and β =0.80 and a correlation coefficient of R^2=0.50. The coefficients of Equation (4) were obtained from the experimental data at a variety of different shear rates and are applicable for a wide range of shear rates.

Influence of shear stress rate

In addition to sea ice flexural and compressive strength, the sea ice shear strength also varies with different loading rates (Timco and Weeks, 2010; Ji et al., 2011). For the level ice in Liaodong Bay of the Bohai Sea, shear strength increases with increasing strain rate but then decreases after reaching a maximum value (Li et al., 2002). Previous studies pointed out that the strain rate and stress rate do not have a significant influence on the shear strength (Saeki and Ono, 1985).

Figure 6 plots a relationship between the sea ice shear strength and the loading rate with a linear fit to the experimental data of

$$\sigma_s = a\dot{\tau} + b \tag{5}$$

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

where $\dot{\tau}$ is the shear stress rate (MPa/s), and a = 7.51 and b =0.28 with a correlation coefficient of R^2=0.54, showing significant influence of shear rate on the sea ice shear strength. The influence of brine volume, however, was not considered in Figure 6 and the test data showed a certain degree of the discrete characteristics (ice crystal structure, salinity, temperature).

Coupling the influences of brine volume and shear stress rate

The single factor analyses above show that the sea ice shear strength is closely related to the ice temperature, brine volume and shear stress rate. A comprehensive multi-factor analysis was performed with the brine volume and shear stress rate as the two main factors considered since brine volume is a function of ice temperature and salinity.

Based on the above analysis, the shear strength is a linear function of stress rate and is an exponential function of brine volume. Thus, a curve is fit to the $\sqrt{\nu_b}$, $\dot{\tau}$ and σ_s data in the form

$$\sigma_s = (a + b\dot{\tau}) \cdot \sqrt{\nu_b}^{(-\beta)} \tag{6}$$

where a, b and β are curve fitting parameters found to be a = 0.21, b = 1.71 and β = 0.473 based on the experimental results and Origin curve-fitting software. The correlation coefficient R^2=0.76, reflects a relationship between σ_s, $\sqrt{\nu_b}$ and $\dot{\tau}$, that is, σ_s increases with the decrease of $\sqrt{\nu_b}$ as a power function, and at the same time increases with the increase of $\dot{\tau}$ as a linear function. The fitted curves and contour lines are shown in Figure 7((a) ~ (c)). Compared with the single factor analysis, Figure 7(b) and (c) reflect the coupling effect of brine volume and stress rate more reasonably.

Eqs. (2), (4) and (5) show the relation between sea ice shear strength and ice temperature, brine volume and shear stress rate, respectively. The shear strength increases with decreasing ice temperature since ice crystals have increased frozen strength on a micro-scale at lower temperatures. With increasing brine volume, the sea ice has more initial pores to reduce the shear strength at a macro-scale. The number of frozen crystals increases with increasing shear rate, which could induce the increase of shear strength on a macro-scale. The sea ice normally performs more like a brittle material under a rapid shear rate. Further studies on shear rate effects will be beneficial to reveal the mechanical properties of sea ice. From Eq. (6), we have a comprehensive view of the influence of brine volume (which is a combination of ice temperature and salinity) and shear rate on shear strength.

Conclusions

Shear failure is one of the typical failure modes of sea ice during the interaction of sea ice with offshore structures and ice breakup in the ice ridging process. Shear strength is a basic mechanical property of sea ice used to study sea ice dynamics. This paper described laterally confined shear strength tests on sea ice samples with a single shear plane. The lateral confinement has little influence on the shear stress with smooth interfaces between the ice sample and the confining plates. The ice samples were collected from Laizhou Bay and the Yellow River Delta of the Bohai Sea. The salinity of ice samples exhibited a wide range from 1‰ to 7‰, which was helpful to analyze the influence of brine volume on shear strength. Experimental results show that sea ice displays a strong variability under the influence of physical characteristics and loading conditions. Sea ice shear strength increases with a decrease in temperature and with an increase in shear rate, both showing approximately a linear relationship. Shear strength also relates

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013; posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

to the square root of brine volume with a negative-power function. Finally, the data was used to establish a function to predict sea ice shear strength based on brine volume and shear stress rate. This study provides a reference for the analysis of sea ice shear strength, which will be a benefit to determine the ice load on offshore structures. Moreover, the relationship between sea ice shear strength, brine volume, and shear stress rate can be applied in the numerical simulation of sea ice dynamics in order to analyze the fracture of ice covers.

Acknowledgements

This study is financially supported by the Special Founding of Marine Commonwealth Industry (No. 201105016, 2012418007) and the National Nature Science Foundation of China (No. 41176012). The authors would like to appreciate the assistance of the colleagues from Dalian University of Technology in the field tests of sea ice physical and mechanical properties. The authors also appreciate the technical and editorial recommendations of the reviewers.

References

Butkovich, T.R. (1959). On the mechanical properties of sea ice, Thule, Greenland, 1957. Snow Ice and Permafrost Research Establishment (SIPRE). U.S. Army Research Report RR54. Wilmetre, IL., USA.

Croasdale, K. R. (2012). Ice rubbling and ice interaction with offshore facilities. *Cold Reg. Sci. Technol.,* 76-77: 37-43.

Fortt, A. L., Schulson, E. M. (2009). Velocity-dependent friction on Coulombic shear faults in ice. *Acta Mater*, 57: 4382-4390.

Frankenstein, G., and Garner, R. (1967). Equations for determining the brine volume sea ice from –0.5℃ to –22.9℃. *J. Glaciol.,* 6(48): 943-944.

Gupta, V., and Bergstrom, J. S. (2002). A progressive damage model for failure by shear faulting in polycrystalline ice under biaxial compression. *Int. J. Plast.,* 18: 507-530.

Ji, S., Wang, A., Su, J., and Yue, Q. (2011). Experimental Studies on Elastic Modulus and Flexural Strength of Sea Ice in the Bohai Sea. *J. Cold Reg. Eng.,* 2011, 25(4): 182-195

Li, Z., Meng G., Gao S. Experimental study of confined shear strength of S2 ice in Liaodong Gulf. *Ocean Eng.,* 2002, 20(1): 20-24. (in Chinese)

Marchenko, A., and Makshtas, A. (2005). A dynamic model of ice ridge buildup. *Cold Reg. Sci. Technol.,* 41:175 – 188

Paige, R. A., and Lee, C.W. (1967). Preliminary studies on sea ice in McMurdo Sound, Antarctica, during Deep Freeze 65. *J. Glaciol.,* 6 (46), 515 – 528.

Pounder, E. R., and Little, E. M. (1959). Some physical properties of sea ice. *Can. J. Phys.,* 37, 443 – 473.

Repetto-Llamazares, Ada, H. V., Høyland K. V., and Evers, K. U. (2011). Experimental studies on shear failure of freeze-bonds in saline ice: Part I: Set-up, failure mode and freeze-bond strength. *Cold Reg. Sci. Technol.,* 65: 286-297.

Saeki, H., and Ono, T. (1985). Experimental study on direct shear strength of sea ice. *Ann. Glaciol.,* 6: 218-221.

Schulson, E. M. (2004). Compressive shear faults within arctic sea ice: Fracture on scales large and small. *J Geophys Res.,* 109, C07016

Strub-Klein, L., and Sudom, D. (2012). A comprehensive analysis of the morphology of first-year sea ice ridges. *Cold Reg. Sci. Technol.,* 82: 94-109.

Timco, G. W., and Weeks, W, F. (2010). A review of engineering properties of sea ice. *Cold Reg. Sci. Technol.,* 60: 107-129.

Whillans, I. M., and Merry, C. J. (2001). Analysis of a shear zone where a tractor fell into a crevasse, western side of the

Ross Ice Shelf, Antarctica. *Cold Reg. Sci. Technol.,* 33: 1–17

Wright, B. D., and Timco, G. W. (2001). First-year ridge interaction with the Molikpaq in the Beaufort Sea. *Cold Reg. Sci. Technol.,* 32: 27–44

Yue, Q., Zhou X., Shen W., et al. (1994). Confined shear test on sea ice. *Journal of Glaciology and Geocryology,* 1994, 16(1): 75-79. (in Chinese)

Zhang M., Meng G., and Yan D. (1995). Shear properties of sea ice in the Bohai Bay and river ice in the Yellow River Delta. *Acta Oceanologica Sinica*, 17(3): 92-95. (in Chinese)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

Fig. 1. Sea ice sampling locations.

Fig. 2. Scheme of sea ice sample and shear test setup.

Fig. 3. Shear force-displacement curve for the sea ice shear strength.

Fig. 4. Influence of ice temperature on sea ice shear strength.

Fig. 5. Influence of brine volume on sea ice shear strength.

Fig. 6. Influence of shear rate on shear strength of sea ice.

Fig. 7. Influence of brine volume and shear rate on sea ice shear strength.

Figure 1

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

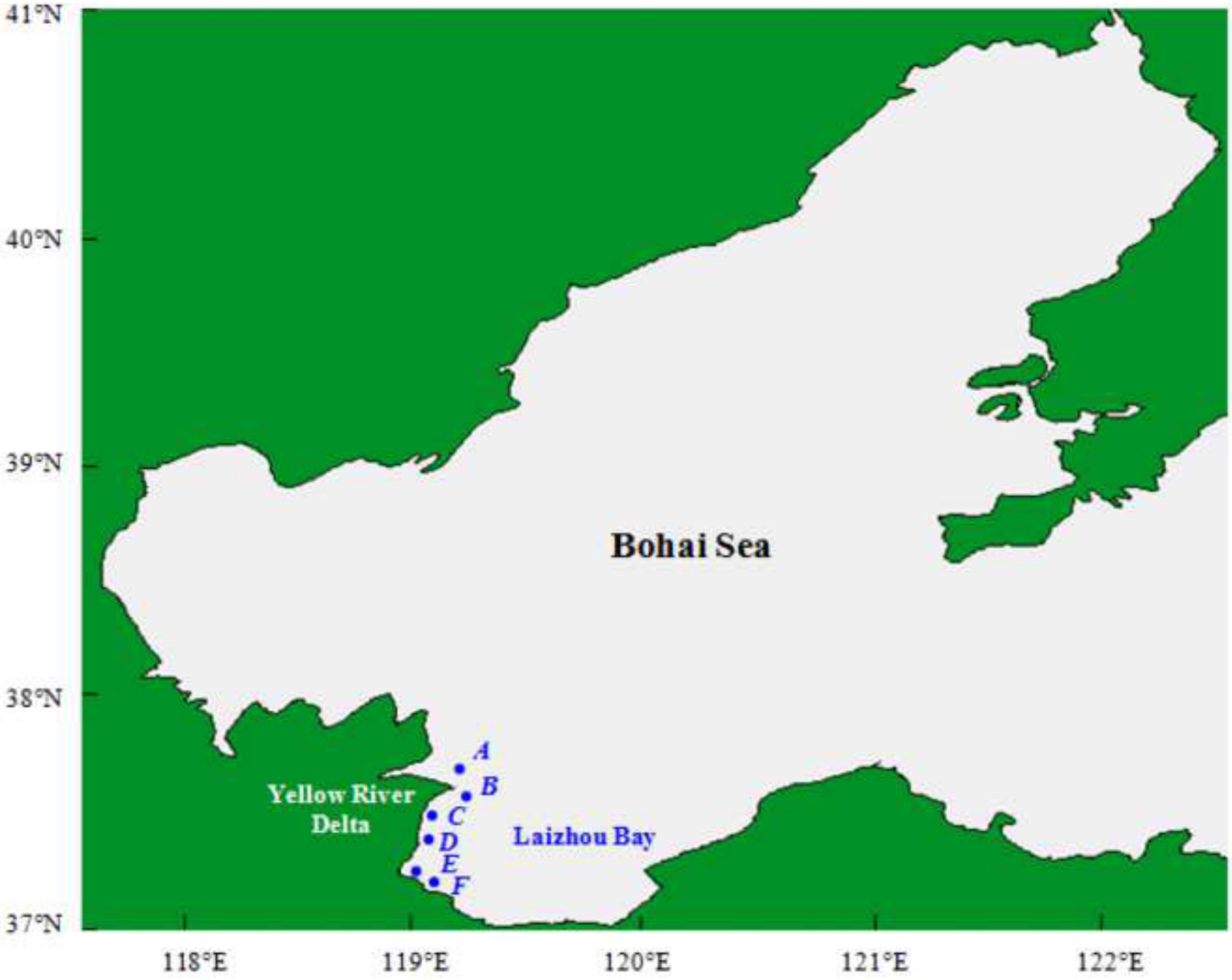


Figure 2(a)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

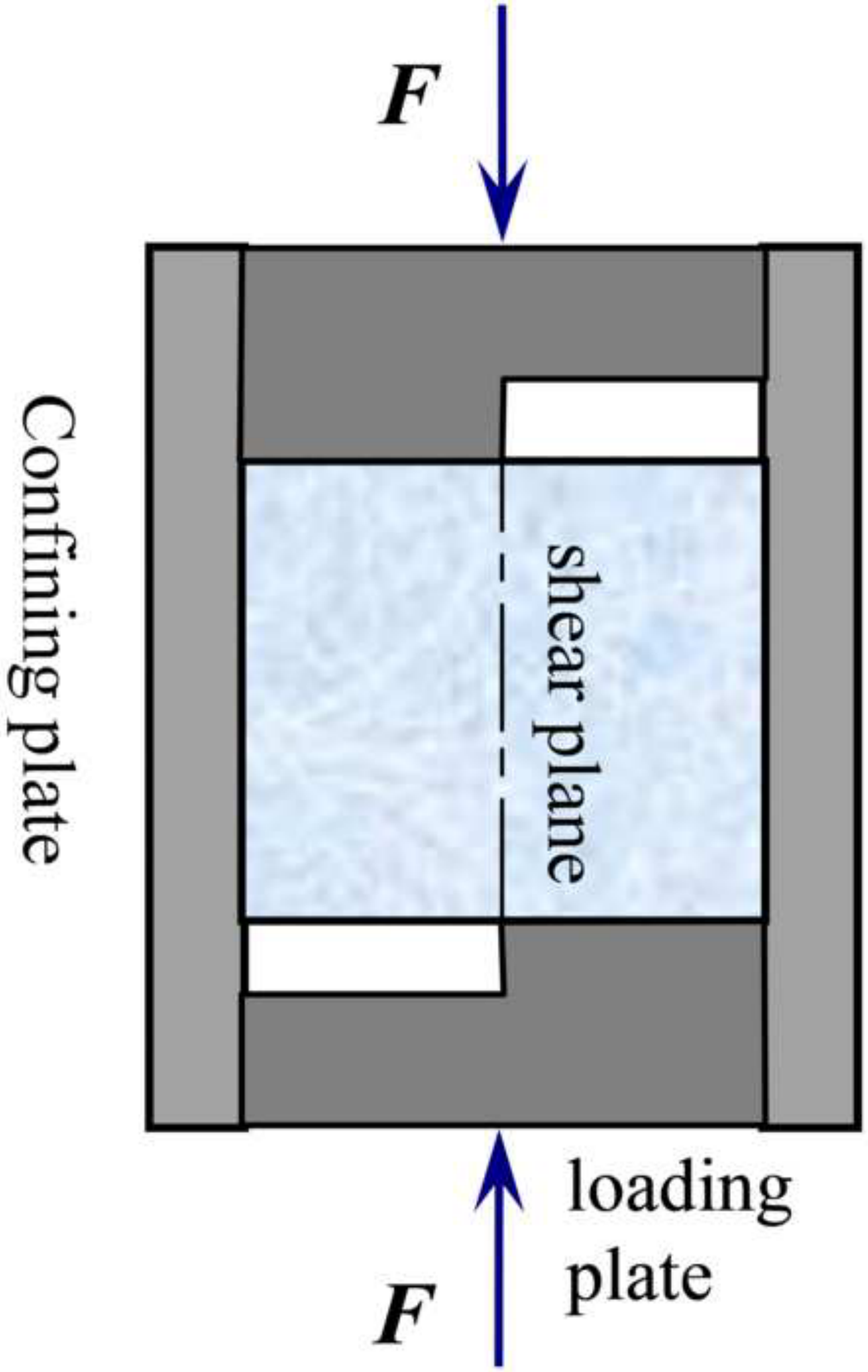


Figure 2(b)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

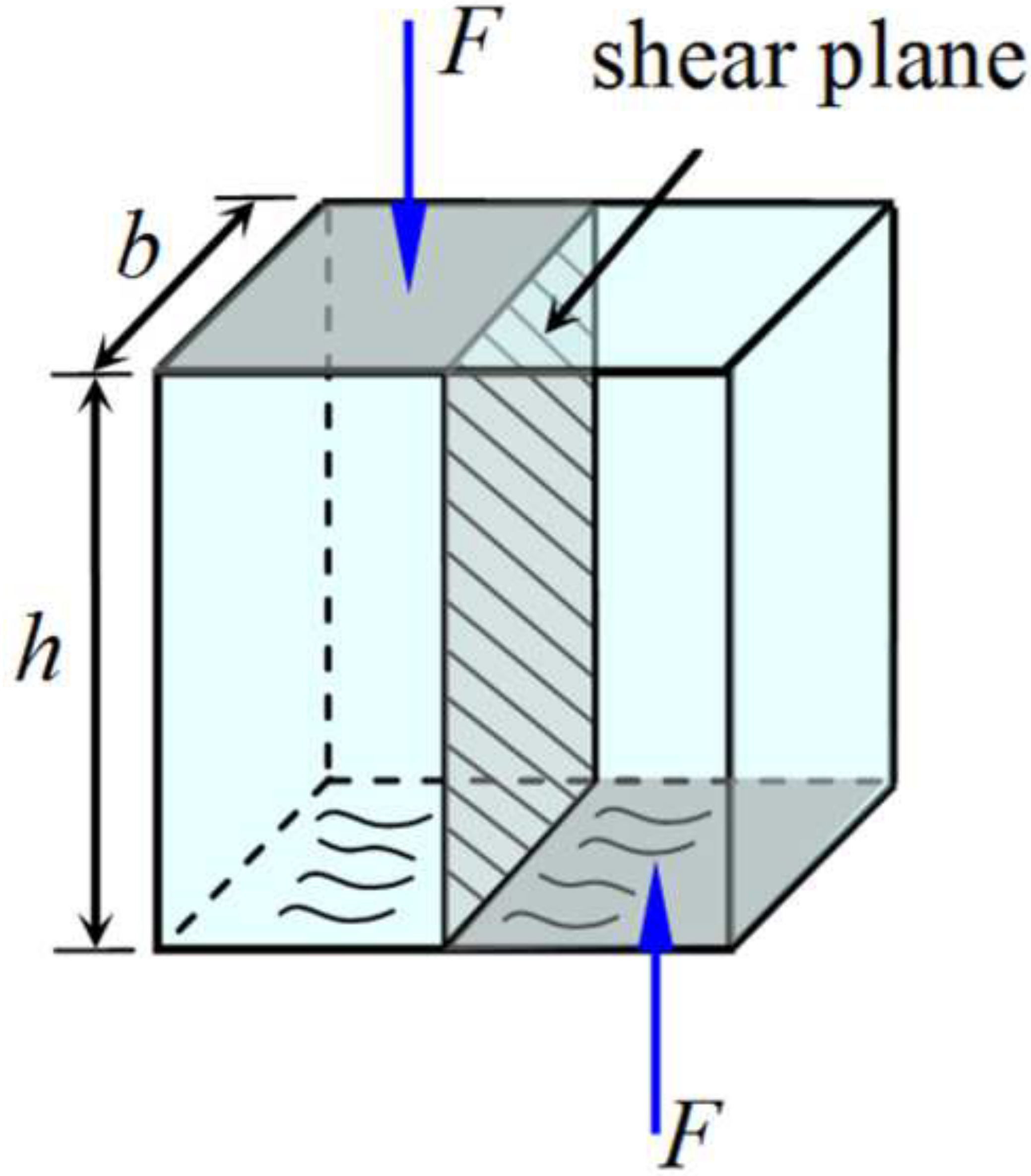


Figure 2(c)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

Figure 3

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

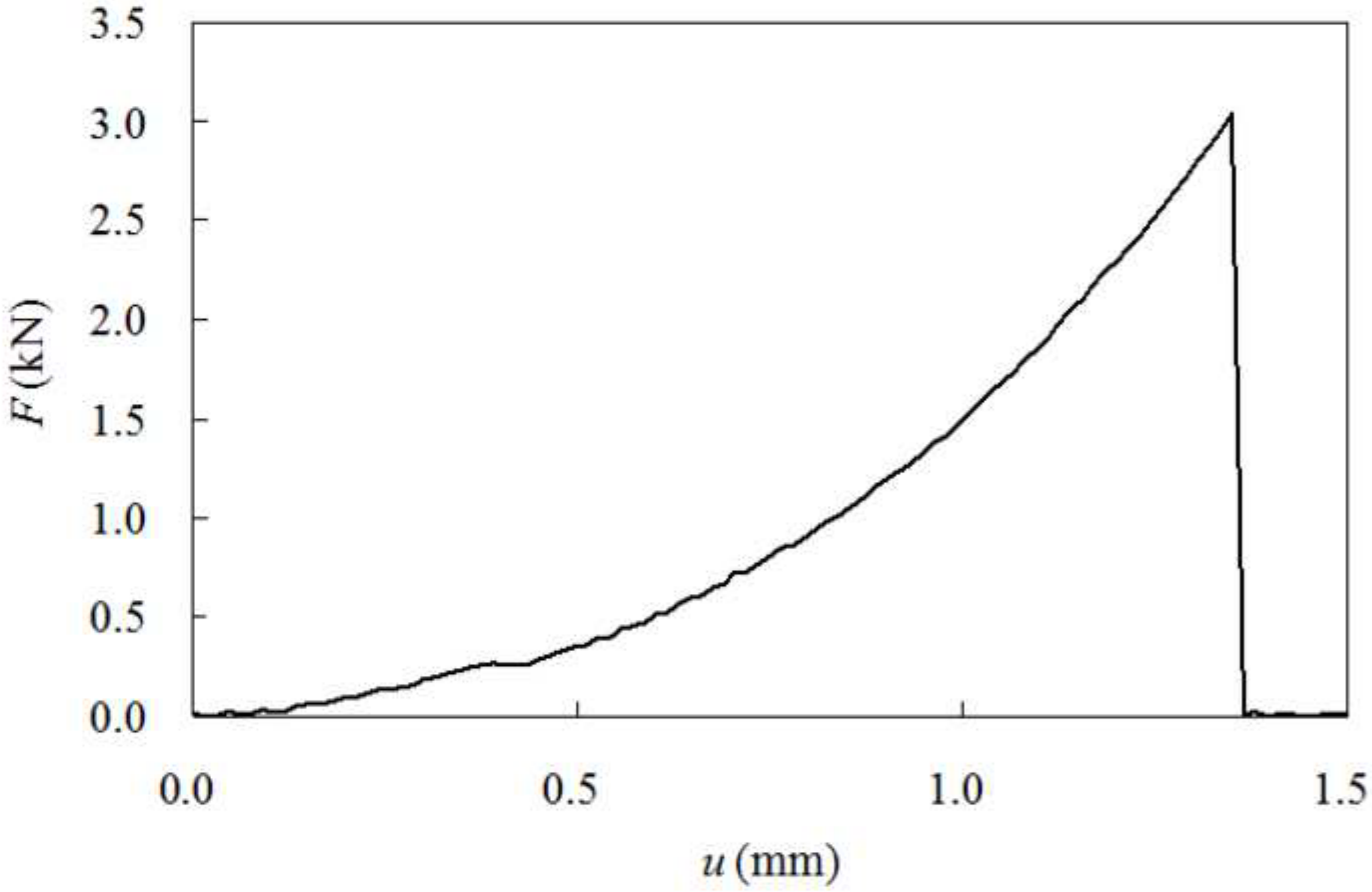


Figure 4

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

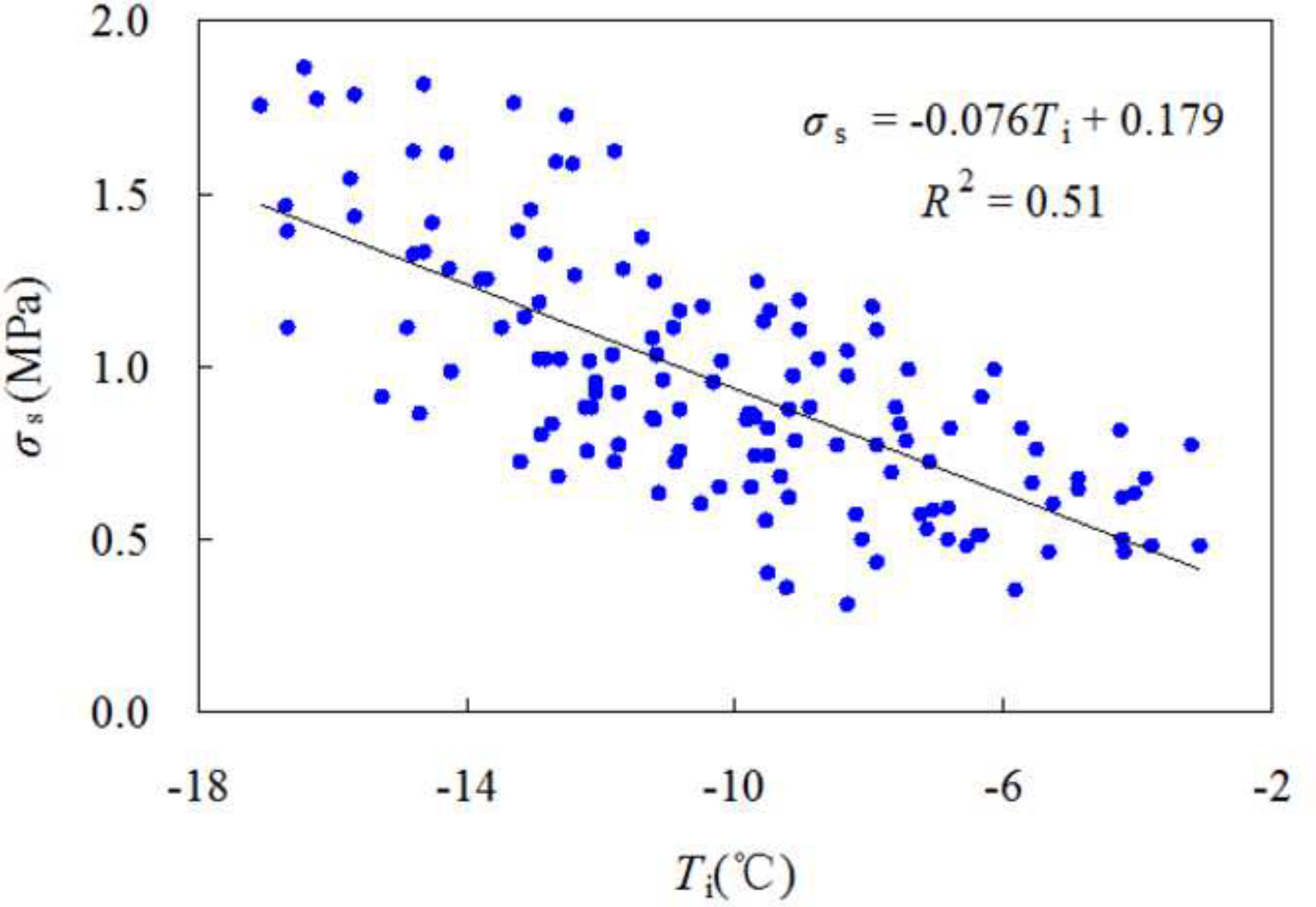


Figure 5

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

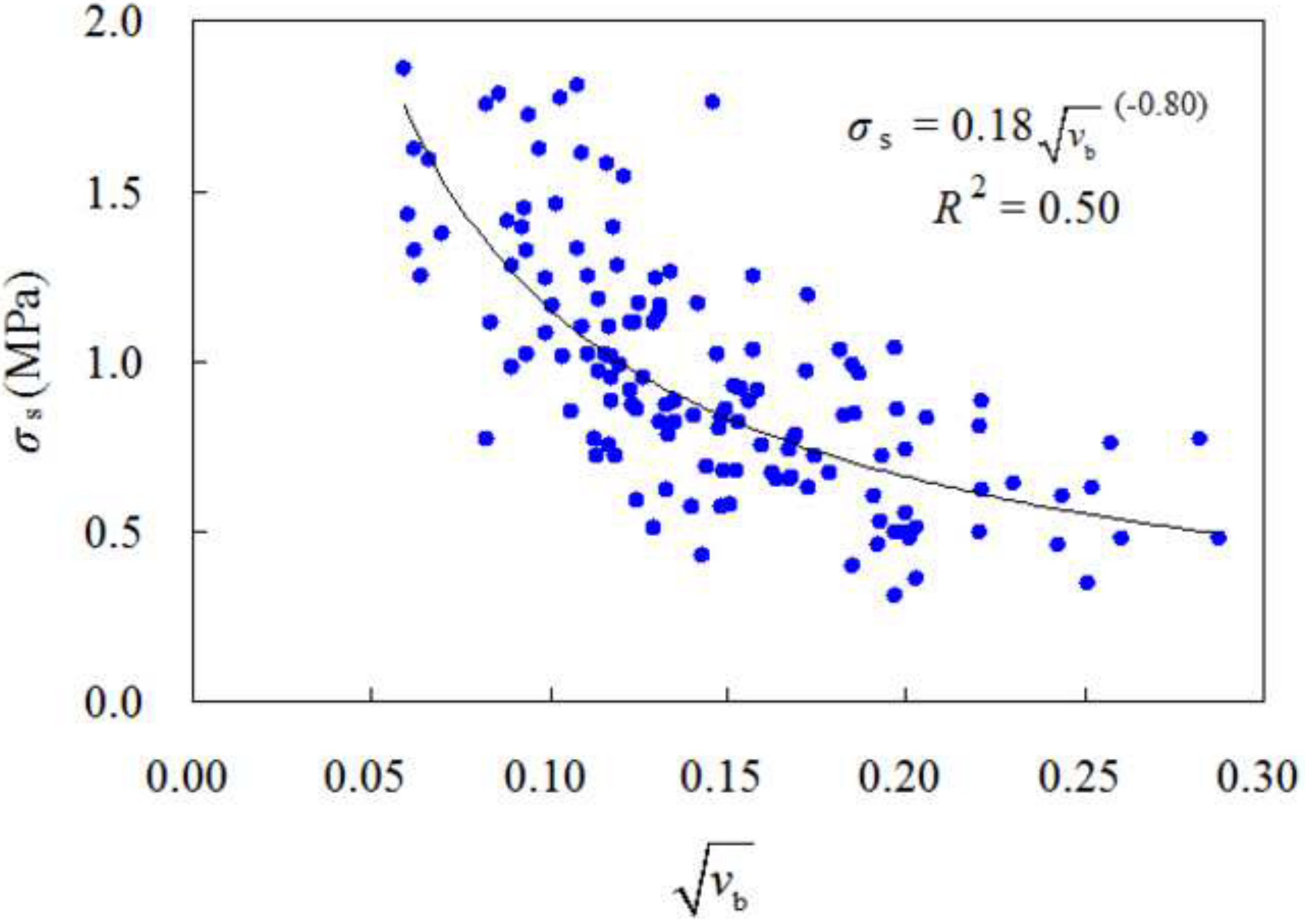


Figure 6

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

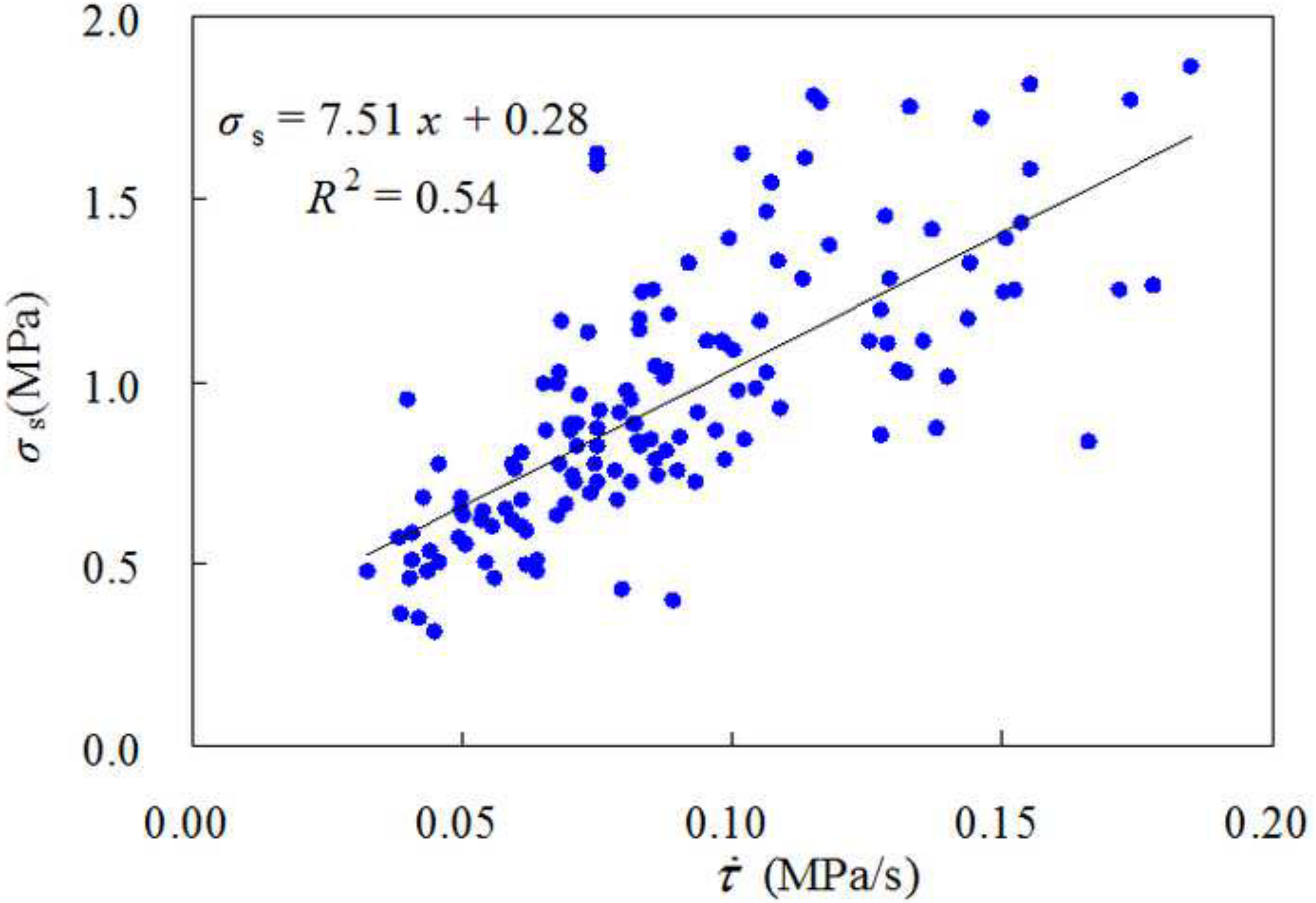


Figure 7(a)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

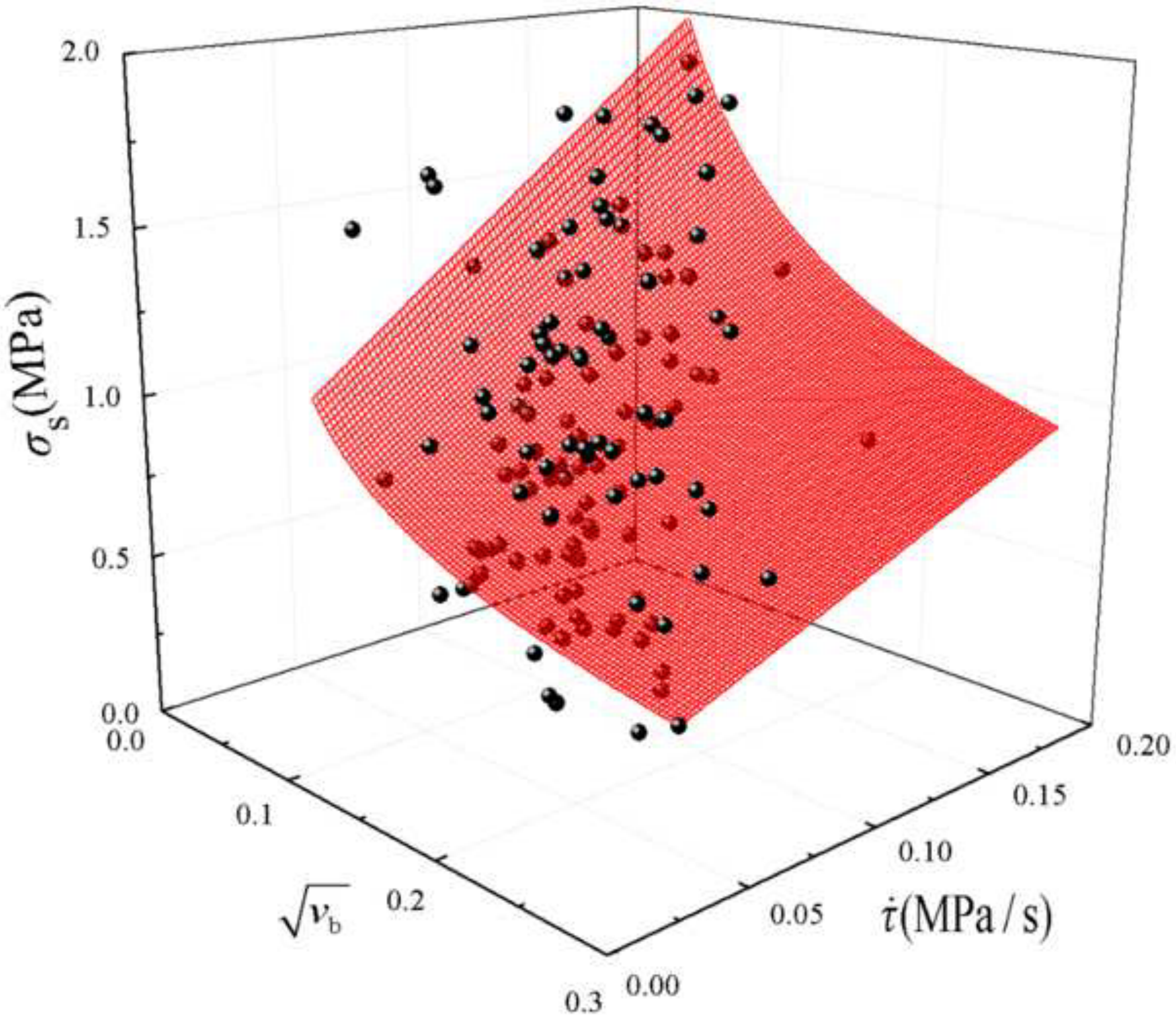


Figure 7(b)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

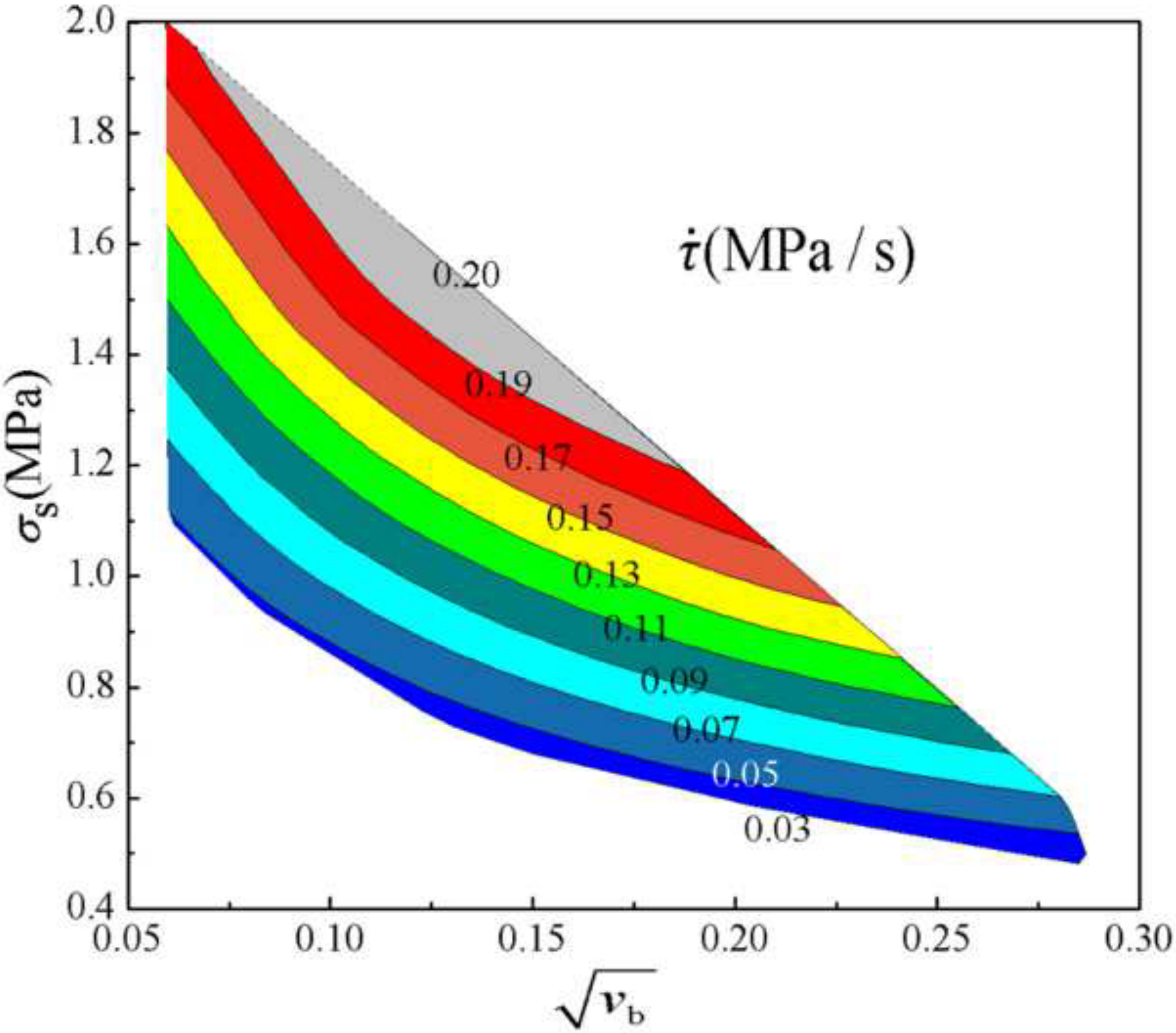
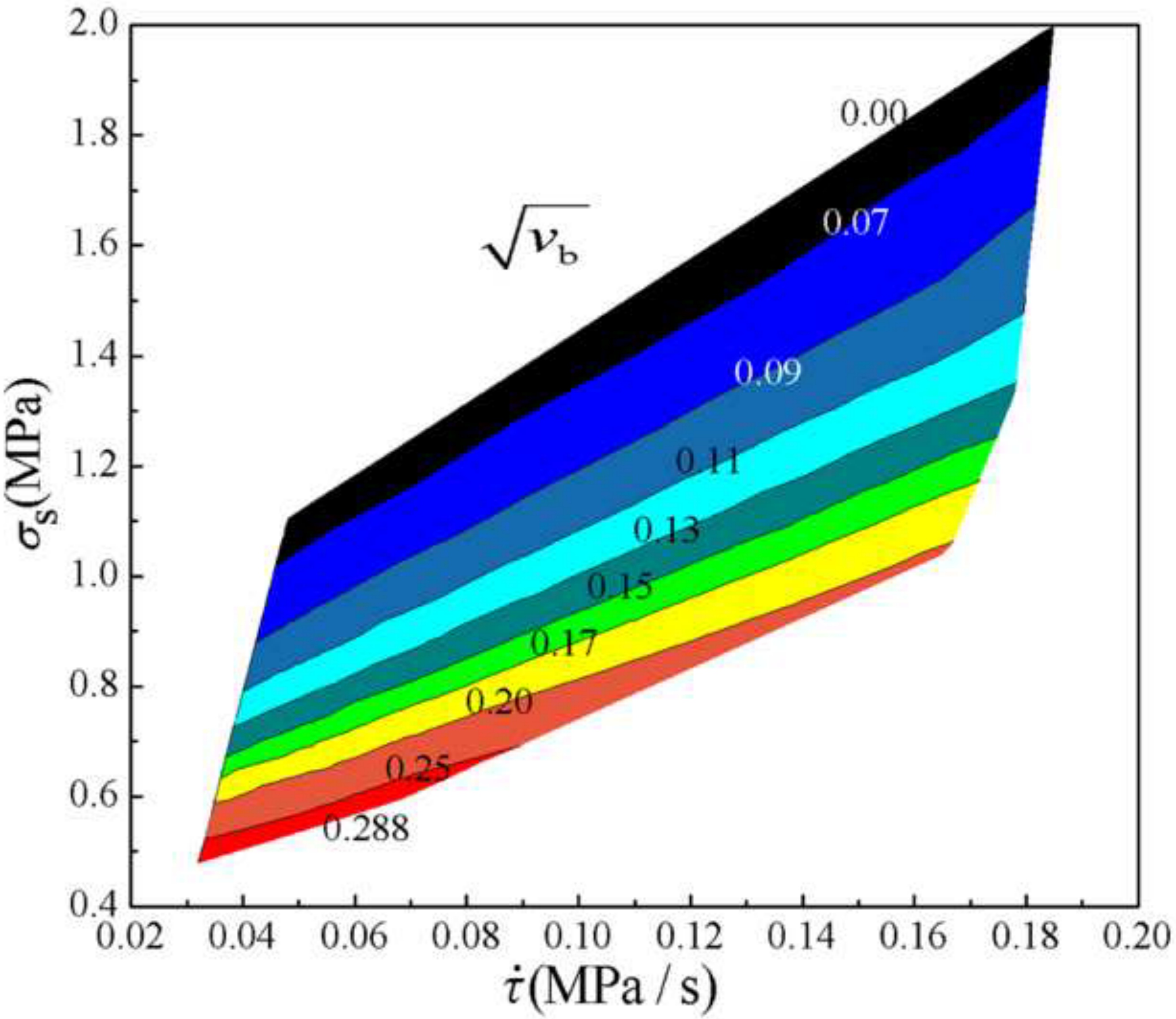


Figure 7(c)

Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060



Journal of Cold Regions Engineering. Submitted August 29, 2012; accepted May 2, 2013;
posted ahead of print May 4, 2013. doi:10.1061/(ASCE)CR.1943-5495.0000060

Table 1. Physical properties of sea ice samples in shear strength tests

Sample collecting sites	*A*	*B*	*C*	*D*	*E*	*F*
Sample number	18	20	38	20	19	12
Mean salinity(‰)	2.06	4.10	3.52	2.13	5.63	6.33
RMSE of salinity(‰)	0.71	1.23	1.04	0.76	0.92	0.85
Mean density(kg/m^3)	910.52	873.28	896.83	931.90	884.98	855.56
RMSE of density(kg/m^3)	10.78	45.53	23.24	16.69	54.36	80.52