ISSMGE TC 202, 2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

Mechanical Properties of Reinforced Soil after Multiple Freeze-Thaw Cycles

Liu Jiankun, Professor

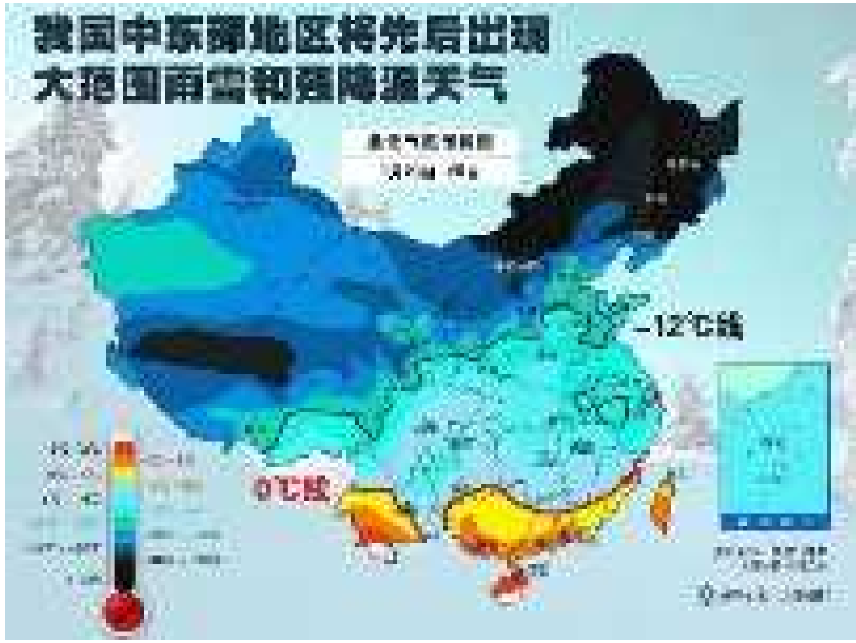
Beijing Jiaotong University

- August 28, 2017， Hokkaido University


ISSMGE TC 202, 1st China-Japan mini workshop: High Speed Railway Geotechnics
北京交通大学路基与基础工程研究所年会
Ballasted track
Slab track

Outline

- Lime-Cement Modified Soil for HSR
- Fiber Reinforced Soil
- Development of Dynamic Direct Shear
- Frost in HSR in China
- Summary



北京交通大學 (原北方交通大学) Beijing Jiaotong University (Northern Jiaotong University)

2nd Japan-China Mini Workshop High Speed Railway Geotechnics

Lime and Cement Modified Soil for Harbin-Dalian HSR

Experimental Study on the Dynamic Properties of Cement- and Lime-Modified Clay Subjected to Freeze-Thaw Cycles.
Cold Regions Science and Technology. Vol.61,No.1(2010),29-33.
Web of Science

2nd Japan-China Mini Workshop High Speed Railway Geotechnics

北京交通大學 (原北方交通大学) Beijing Jiaotong University (Northern Jiaotong University)

Critical Dynamic Stress

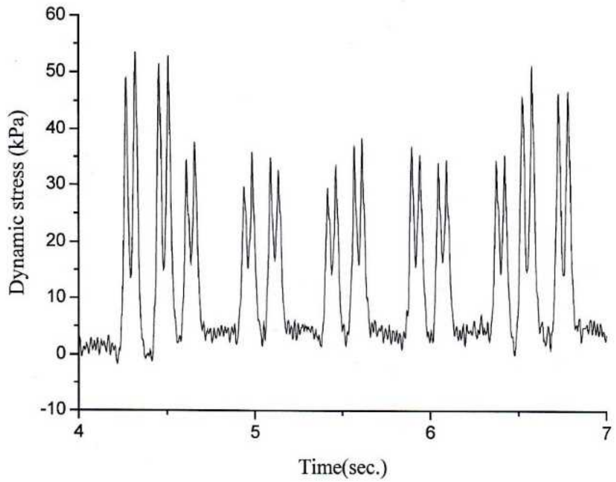
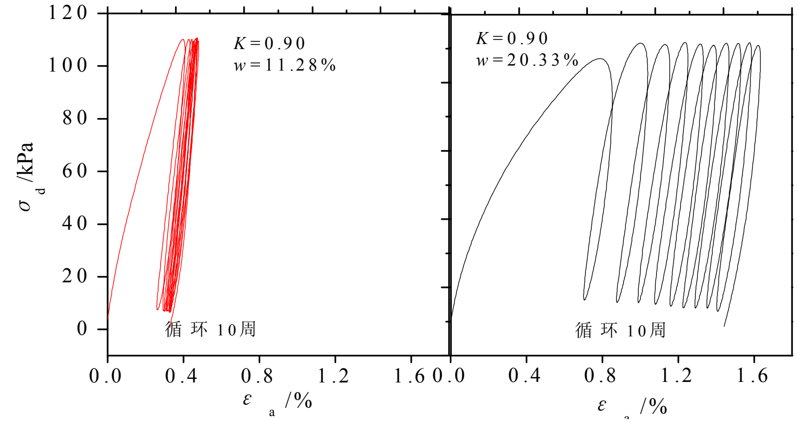
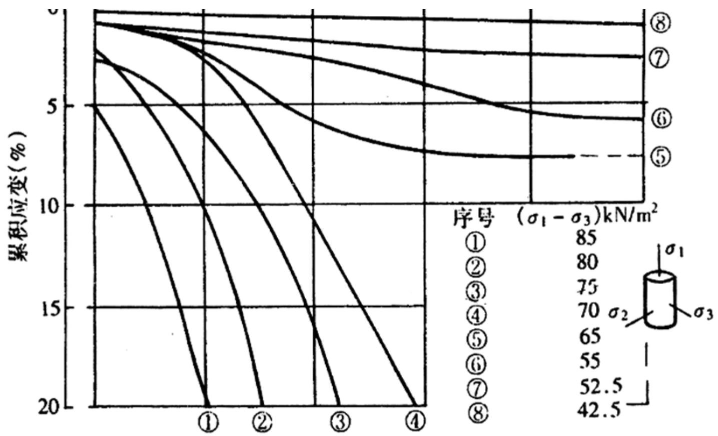


Fig. 1 Typical dynamic stress shape on subgrade surface





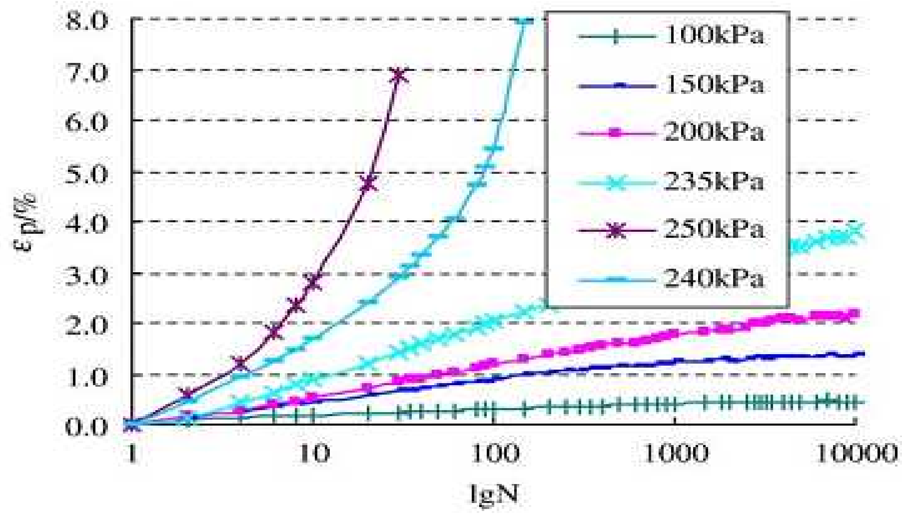


Fig. 5. ε_p-lgN curves of clay soil (20 kPa).

2nd Japan-China Mini Workshop High Speed Railway Geotechnics

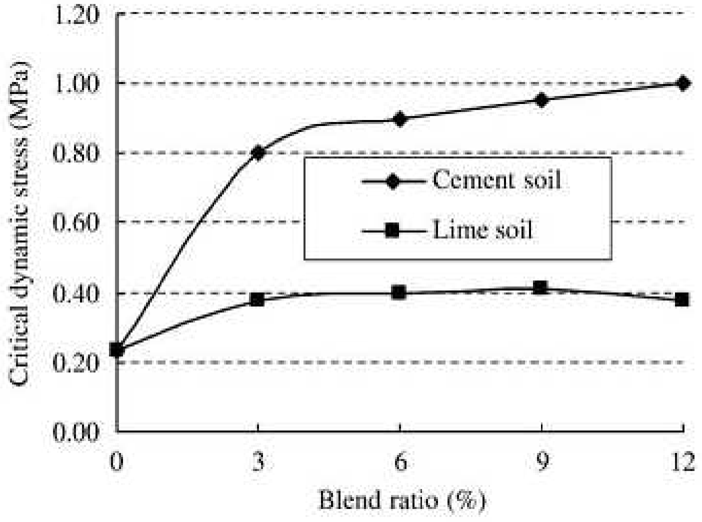


Fig. 6. Critical dynamic stress vs. blend ratio (20 kPa).

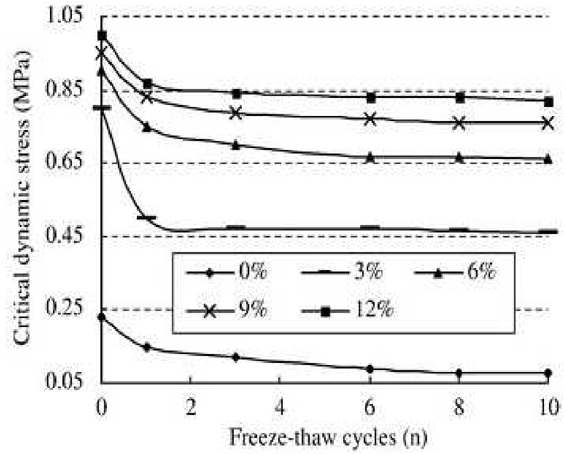


Fig. 7. Critical dynamic stress of cement-modified soil and clay vs. freeze–thaw cycles (confining pressure is 20 kPa).

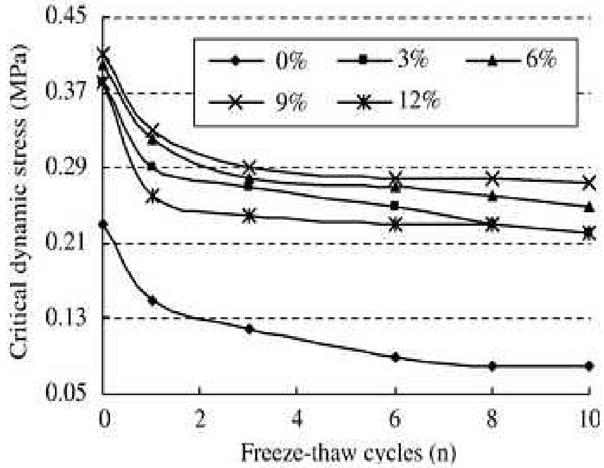


Fig. 8. Critical dynamic stress of lime-modified soil and clay vs. freeze–thaw cycles (confining pressure is 20 kPa).

$$\eta_f = 1 - \frac{\sigma_{dcrb} - \sigma_{dcra}}{\sigma_{dcrb}},$$

- where σ_{dcrb} is the critical dynamic stress before a freeze-thaw cycle, and σ_{dcra} is the critical dynamic stress after a freeze-thaw cycle.

Table 3
Critical dynamic stress attenuation coefficient of modified soil and clay subjected to freeze–thaw cycles.

Freeze–thaw number	Critical dynamic stress attenuation coefficient of cement soil				Clay soil
	3%	6%	9%	12%	
1	0.63	0.83	0.87	0.87	0.65
3	0.59	0.78	0.83	0.84	0.52
10	0.58	0.73	0.80	0.82	0.35

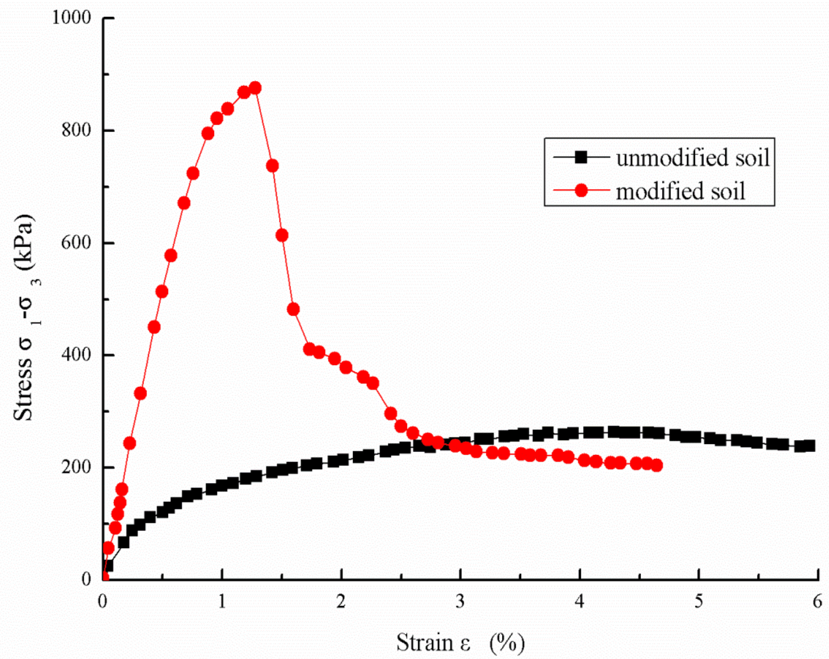
Freeze–thaw number	Critical dynamic stress attenuation coefficient of lime soil			
	3%	6%	9%	12%
1	0.76	0.80	0.80	0.68
3	0.71	0.70	0.71	0.68
10	0.58	0.63	0.67	0.68

Experimental Study on the Dynamic Properties of Cement- and Lime-Modified Clay Subjected to Freeze-Thaw Cycles. Cold Regions Science and Technology. Vol.61,No.1(2010),29-33. Web of Science

2nd Japan-China Mini Workshop High Speed Railway Geotechnics

The effect of freeze-thaw cycles on the static properties of modified Clay using Solidifying Agent

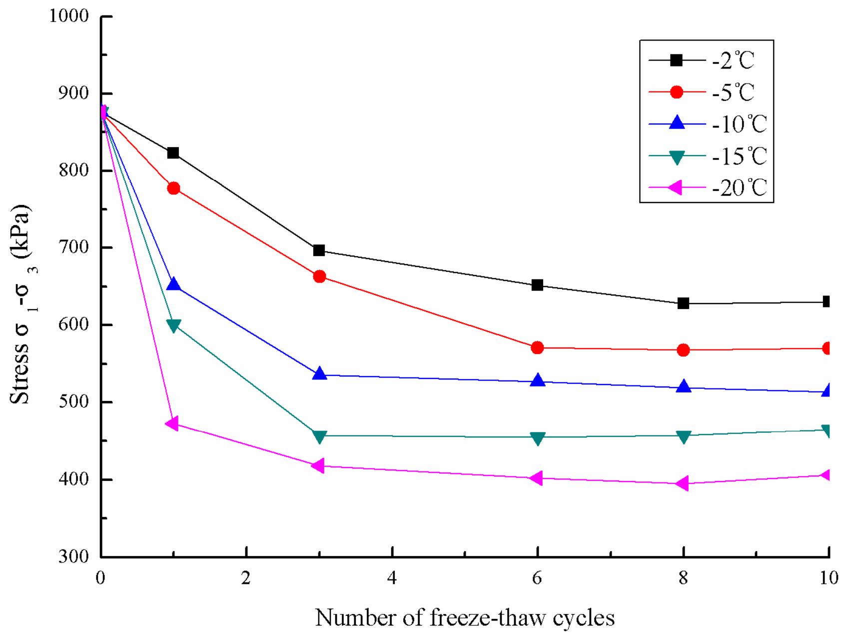
- Solidifying Agent, "Aught-Set" 3%,
- Freezing Temperature: -2°C, -5°C, -10°C, -15°C, -20°C
- Confining Pressure 20KPa



- The static strength of unmodified soil is 262kPa.
- the static strength of modified soil is 876kPa.

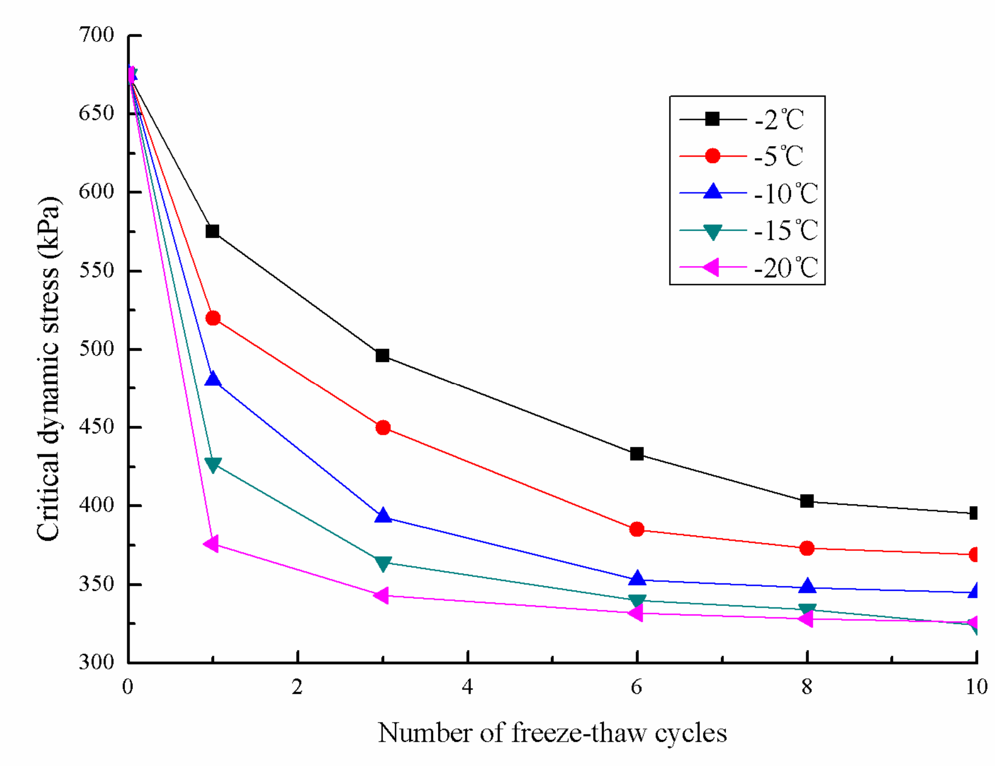
2nd Japan-China Mini Workshop High Speed Railway Geotechnics

The effect of freeze-thaw cycles on the static properties of modified Clay using Solidifying Agent



- The static strength of modified soil with different number and negative temperature of freeze-thaw cycles

The effect of freeze-thaw cycles on the dynamic properties of modified soil

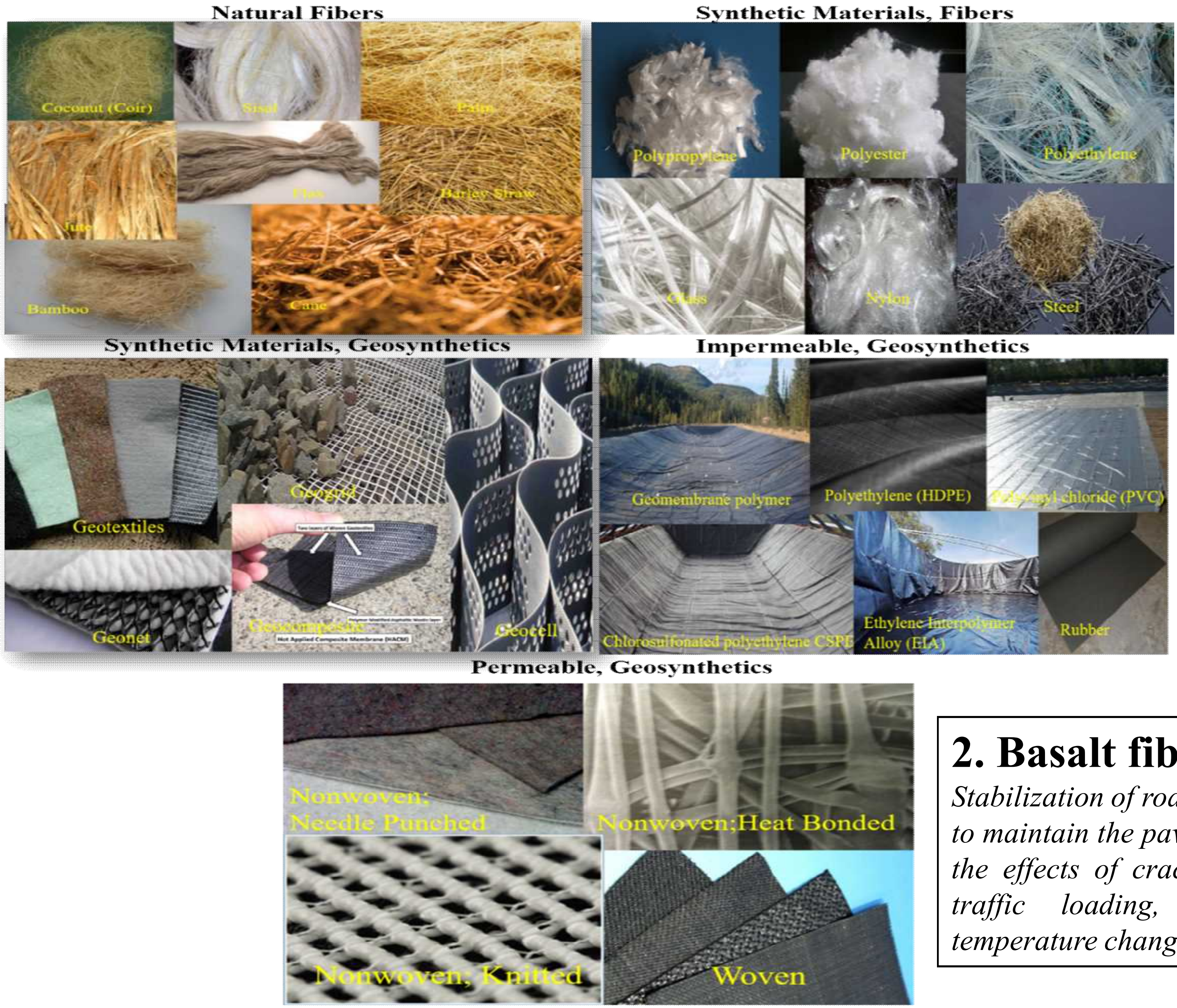


- The relationship between critical dynamic stress, CDS and the freeze-thaw cycles

北京交通大學
（原北方交通大学）
Beijing Jiaotong University
(Northern Jiaotong University)

Freeze-Thaw Effect on Fiber-Reinforced Soil

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics



- **Long service life,**
- **Light weight**
- **Increase strength**
- **Lower therml conductivity**

1. Glass fiber

Effective bulk density, hardness, stability, and flexibility and stiffness.

2. Basalt fiber

Stabilization of road and highway to maintain the pavement life by decreasing the effects of cracks caused by excessive traffic loading, age hardening and temperature changes.

北京交通大學 (原北方交通大学) Beijing Jiaotong University (Northern Jiaotong University)

	Soil Properties	w_{opt} (%)	LL (%)	PI (%)	MDD (gr/cm³)	Grain Composition* (%)			
						d>0.01	0.01 ≥d≥0.005	0.005≥d>0.005	d≤0.001
R1	-Physical properties -Mass loss -Changes of water content -Static triaxial test	12.9	30.04	12.09	1.93	78.87	7.96	7.30	5.86
R2	-Physical properties -Changes of height -Thermal conductivity test -Dynamic triaxial test	18.3	28.29	8.05	1.80	67.29	11.16	15.95	5.59

*Classified as CL according to

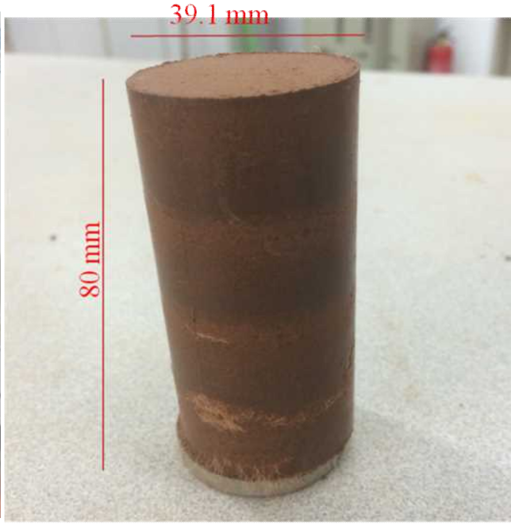
	Basalt Fiber	Glass Fiber
Fiber Properties	Values	Values
Modulus of elasticity	86.2 GPa	74 GPa
Breaking extension	3.1 %	4.7 %
Fiber diameter	10 µm	10 µm
Linear density	60-4,200 tex	40-4,200 tex
Length	15 mm	15 mm
Tensile strength	3920 MPa	3450 MPa
Thermal conductivity	0.03 W/m·K	0.04 W/m·K

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

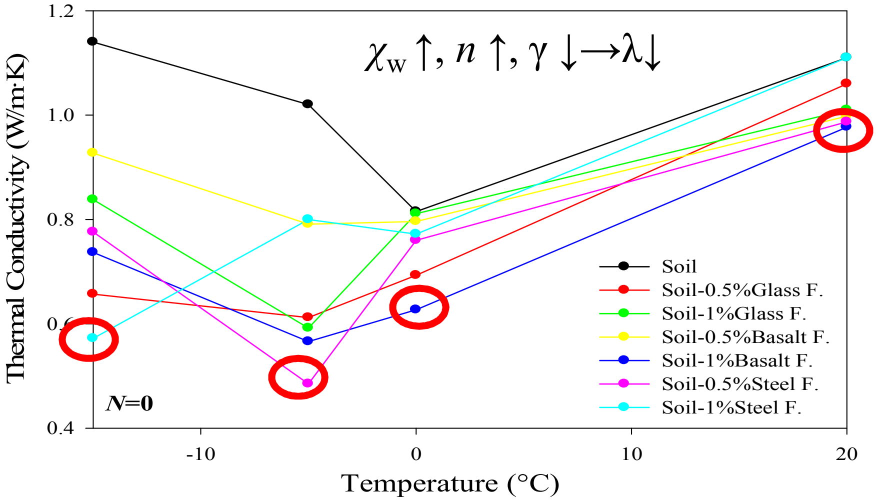
Materials	(χ_w)
Glass Fiber (GF) Basalt Fiber (BF)	0%, 0.5%, 1% 0%, 0.5%, 1%
Glass Fiber (GF) Basalt Fiber (BF)	0%, 0.5%, 1% 0%, 0.5%, 1%
Glass Fiber (GF) Basalt Fiber (BF)	0%, 0.5%, 1% 0%, 0.5%, 1%

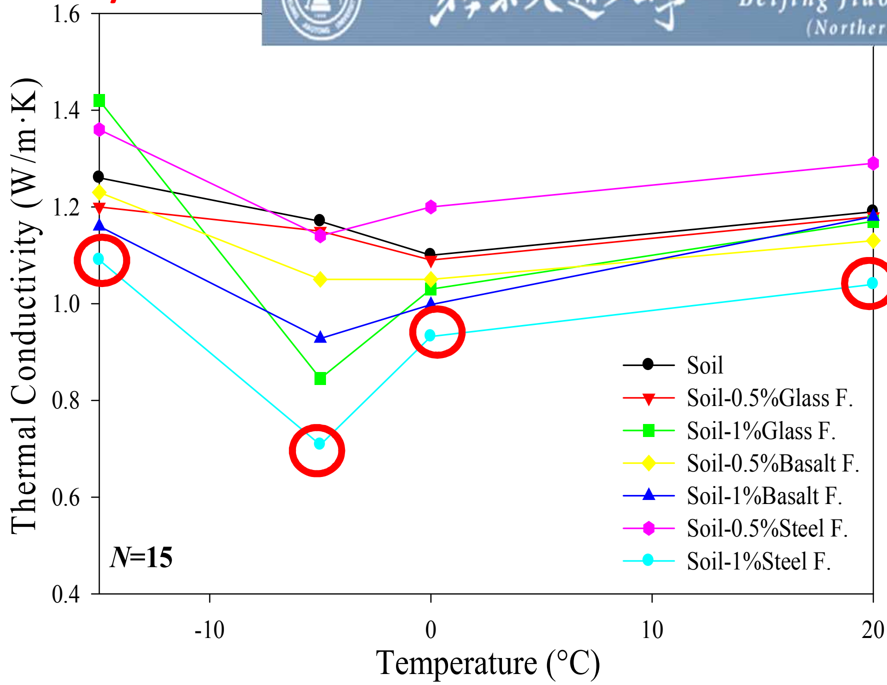
Series	Number of specimen	Dimension of test specimen (mm)		Freeze-thaw cycles	Temperature		Tested Temperature
		Height	Diameter		Freezing	Thawing	
Mass loss	12	80	39.1	0, 15	-20 ºC	20 ºC	~20 ºC
Change of water content	12	80	39.1	0, 2, 5, 10, 15	-20 ºC	20 ºC	~20 ºC
Change of height	12	80	39.1	0, 2, 5, 10, 15	-15 ºC	20 ºC	~20 ºC
Thermal conductivity test	60	60	61.8	0, 2, 5, 10, 15	-15 ºC	20 ºC	20ºC, 0ºC, -5ºC, -15ºC
Static triaxial test	150	80	39.1	0, 2, 5, 10, 15	-20 ºC	20 ºC	~20 ºC
Dynamic trixial test	150	125	61.8	0, 2, 5, 10, 15	-15 ºC	20 ºC	~20 ºC



2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

Thermal conductivity of fiber-reinforced soil



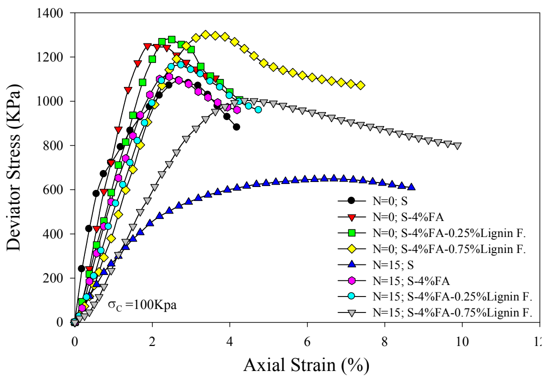


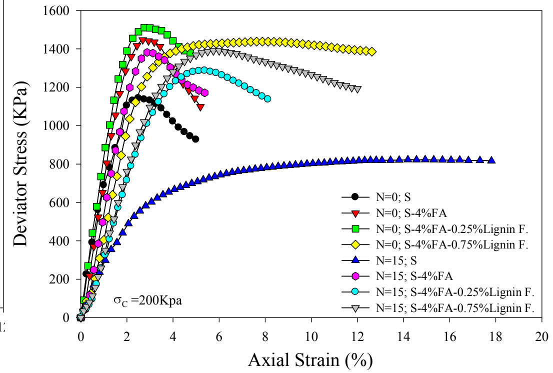
Dry density
Porosity
Saturation degree

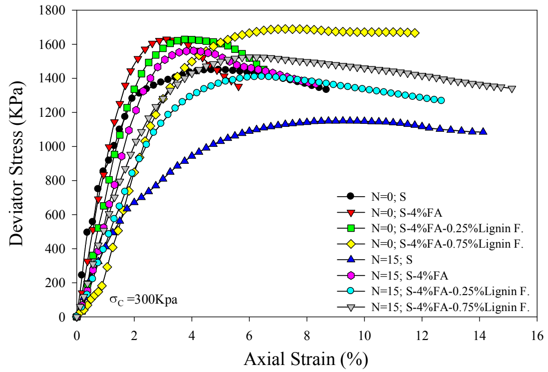
Heat storage capacity,
Saturation degree,
Fiber dispersion in the mixture and fiber type (unwoven or woven)
Presence unfrozen water

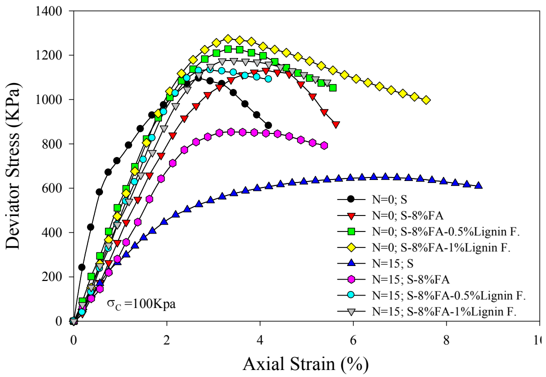
$\lambda_{frozensoil} > \lambda_{unfrozensoil} \rightarrow \lambda_{ice} > \lambda_{water}$

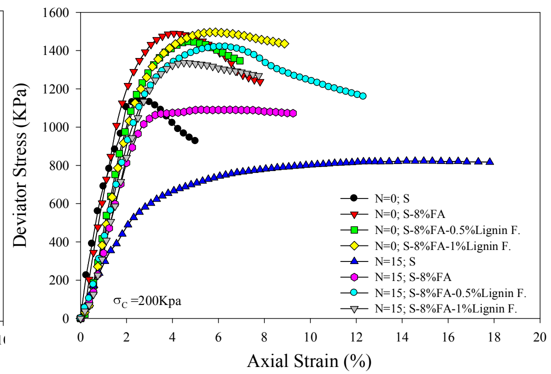
- As $T\downarrow \rightarrow$ ice content in the soil $\uparrow$, *the density of the ions changes* in the phase boundary.
- During the thawing process, exchange cations exhibit the behavior of rehydration.
- $\gamma \uparrow \rightarrow \lambda \uparrow$

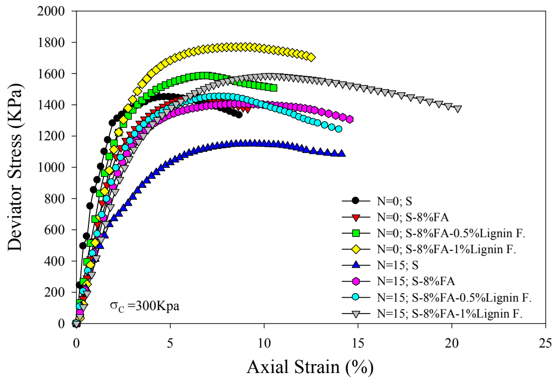












Static UU Triaxial

No	σ_c	χ_w	*4FA*	*8FA*	*N*	$(\sigma_1 - \sigma_3)_{max}$
1	→	0	↑	0	0	↑
2	→	0	0	↑	0	↑
3	→	↑	↑	0	0	↑
4	→	↑	0	↑	0	↑
5	↑	0/ ↑	↑	↑	0	↑
6	→	0	↑	0	↑	→
7	→	0	0	↑	↑	↑
8	→	↑	↑	0	↑	↑
9	→	↑	0	↑	↑	↑

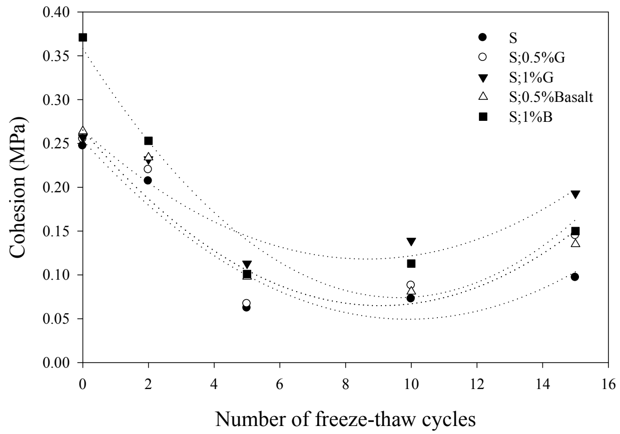
2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

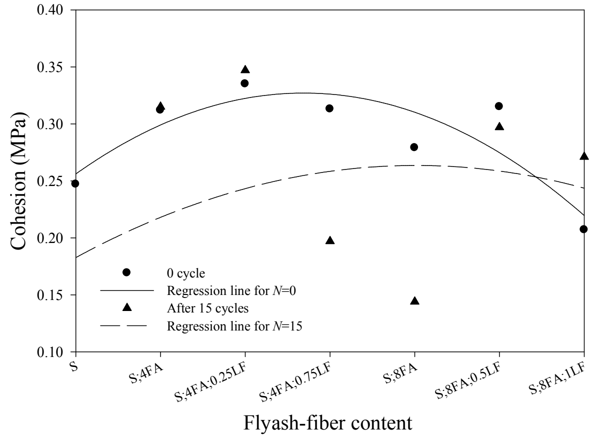
北京交通大學 （原北方交通大学） Beijing Jiaotong University (Northern Jiaotong University)

Static UU Triaxial

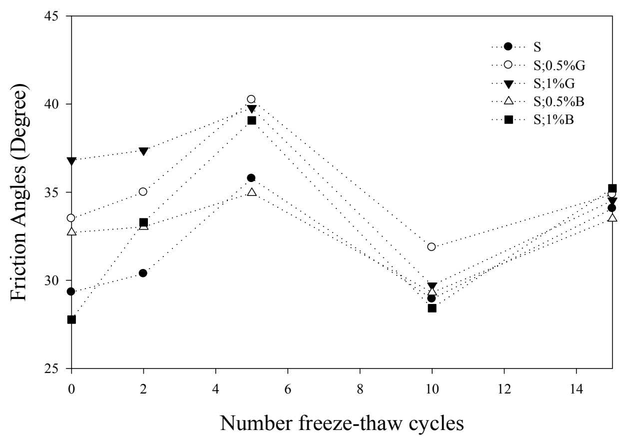
Cohesion and friction angles

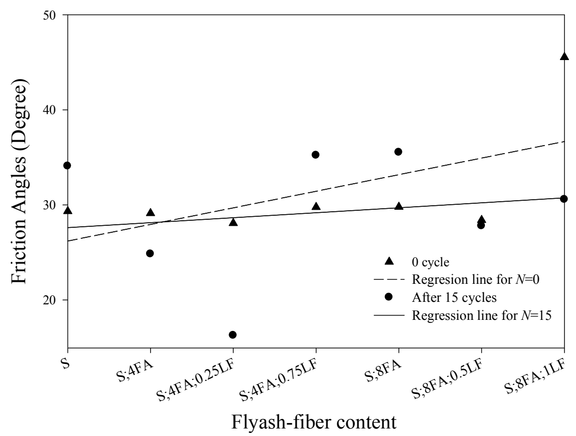
2nd Japan-China Mini Workshop on High Speed Railway Geotechnics





	Reduction ratio of cohesion		***Reduction ratio of cohesion***
0.5% GF	43%	8% FA	48%
1% GF	25%	4% FA-0.75 %LF	37%
0.5% BF	49%	8% FA-0.5 %LF	6%
1% BF	59%		





$\phi\uparrow$, $w\downarrow$

$N\uparrow$, $w\downarrow$

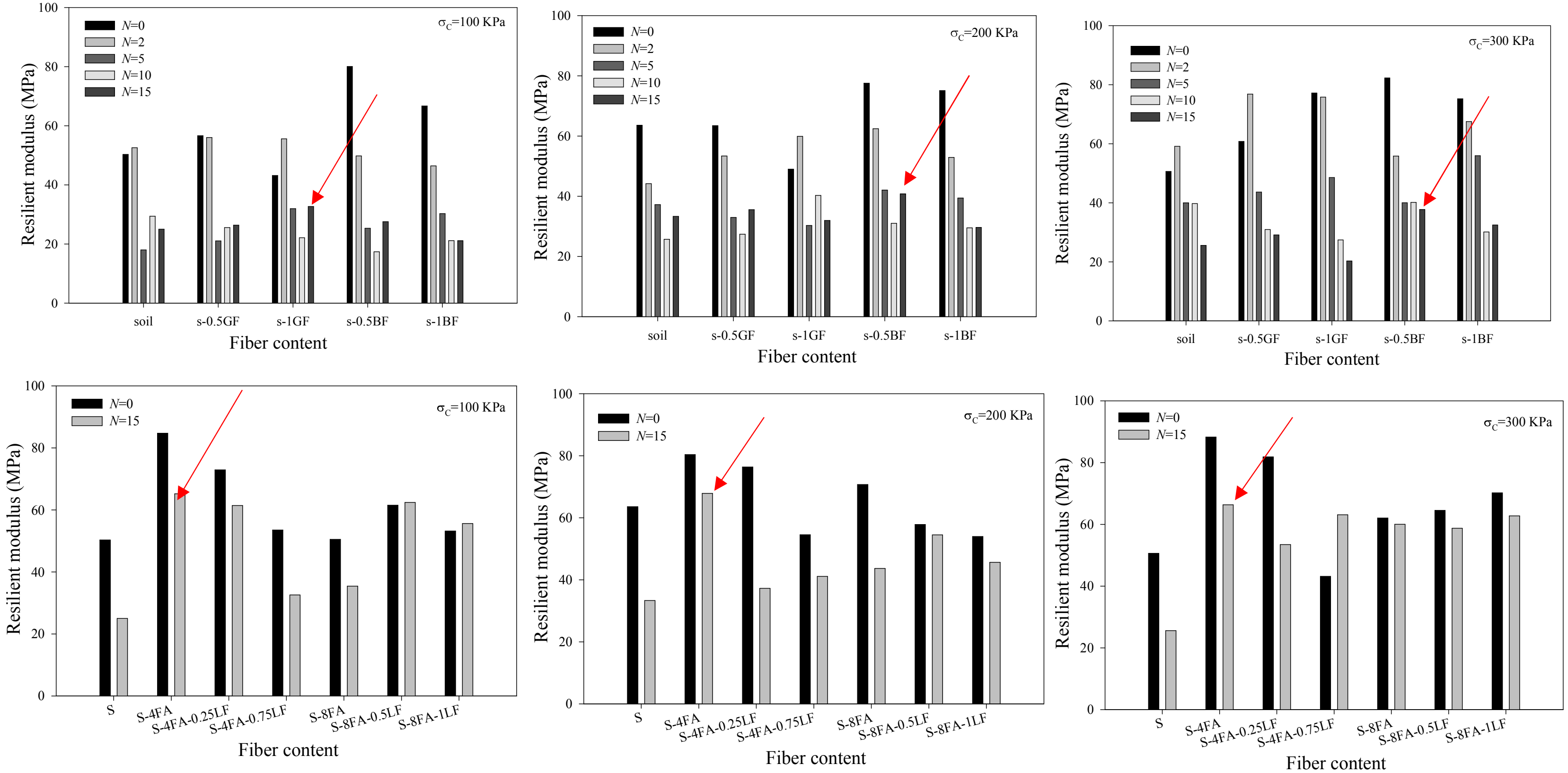
and N=10 w steadied.

$\phi\uparrow$, $N\uparrow$

Static UU Triaxial

Resilient modulus $E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{1.0\%} - \sigma_0}{\varepsilon_{1.0\%} - \varepsilon_0}$

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

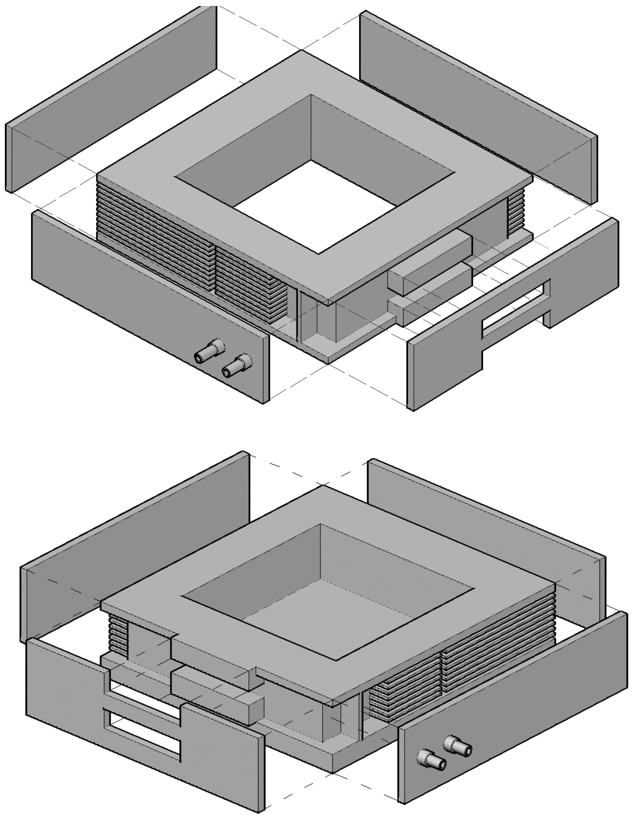


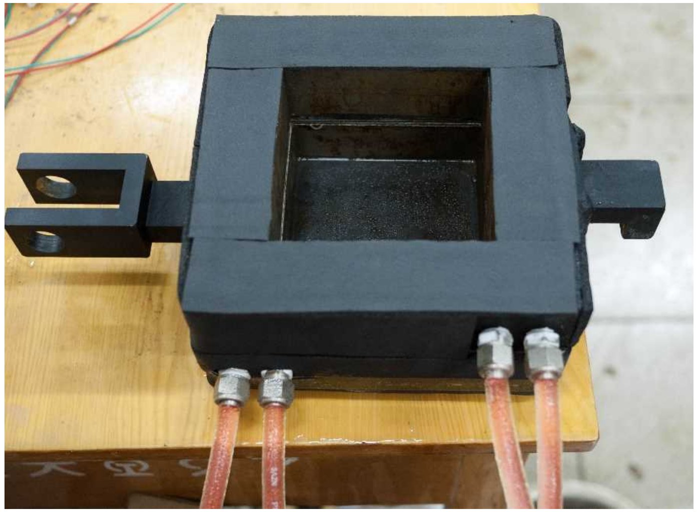
a resilient modulus < 55 kPa → negligible freeze-thaw effects
a resilient modulus> 103 KPa → a decrease of more than 50 %

Development of Dynamic Direct Shearing Box

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

Dynamic direct shear test —— Temperature-controlled shear box



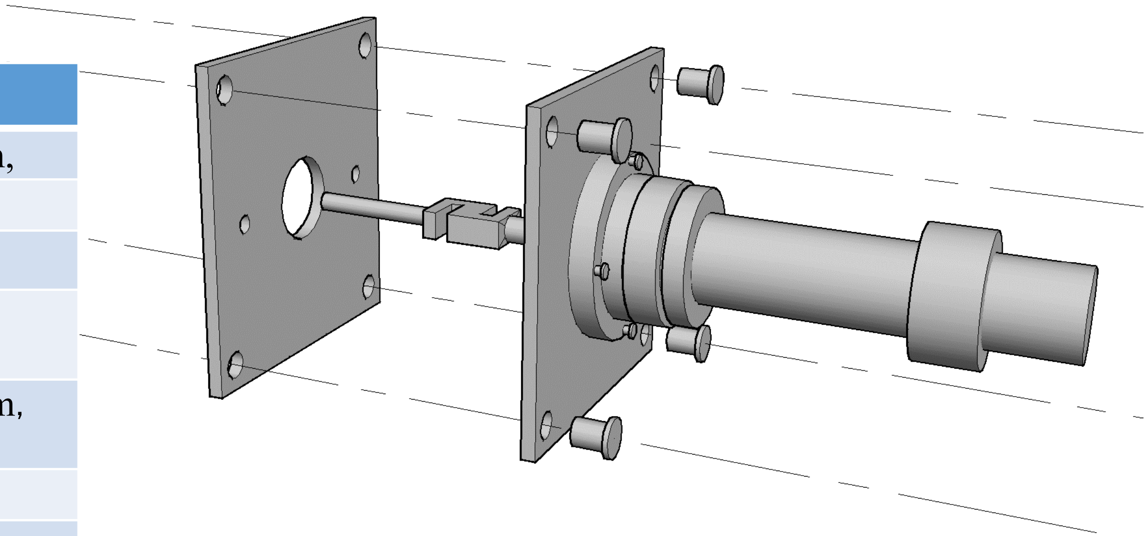


Schematic of temperature-controlled direct shear box

Dynamic direct shear test ——
Dynamic actuator and connect to the workbench

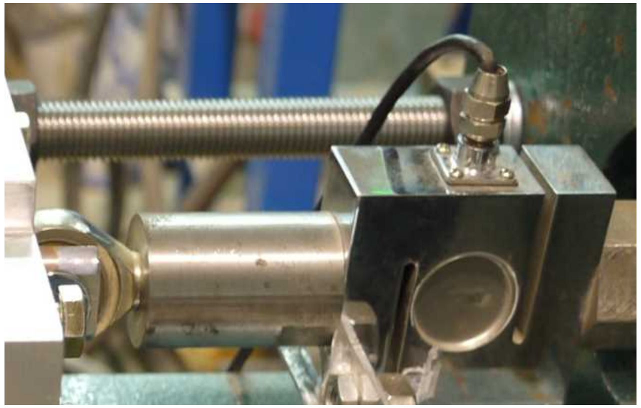
Design Project	Load amplitude range (kN)	Piston stroke (mm)	Vibrational frequency (Hz)
Performance Parameters	1～20kN	-50mm～50mm	0.5～5

Unit name	Performance Parameters
Variable pump	Working pressure:7.0MPa, maximum flow:72L/min, System accuracy of filtration 25μ
Pump motor	Motor power:15kW
Servo valve	Deflector jet valve: SFL223, no-load flow under 7MPa:60L/min
Actuator	Rated working pressure :7MPa, Piston stroke: 200mm, Piston diameter:70mm, Rod diameter:32mm
Fuel tank	Capacity:500L
Cooling tank	Water Cooling, column tubular oil cooler:2LQFL, Structural style: Tube-fin condenser, Cooling area:0.65m2, Working Pressure:1MPa, Oil pressure drop≤0.1MPa, Water pressure drop≤0.015MPa, Working temperature of water:25~30℃, Working temperature of oil≤100℃。



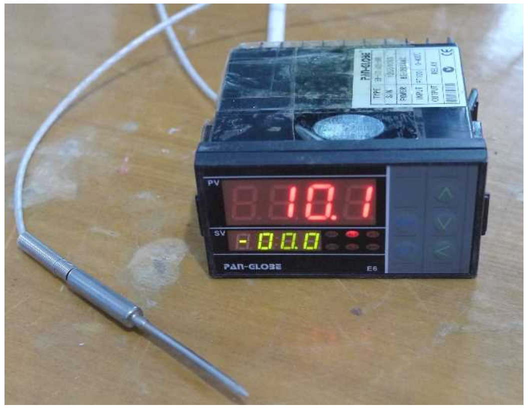
Design of the actuator

Dynamic direct shear test ——
Measuring system

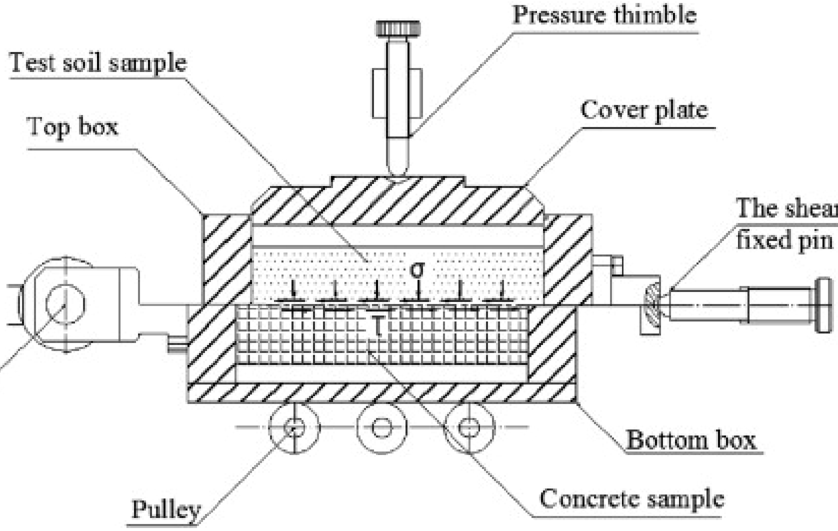


Displacement and Force Measuring Devi̇ce

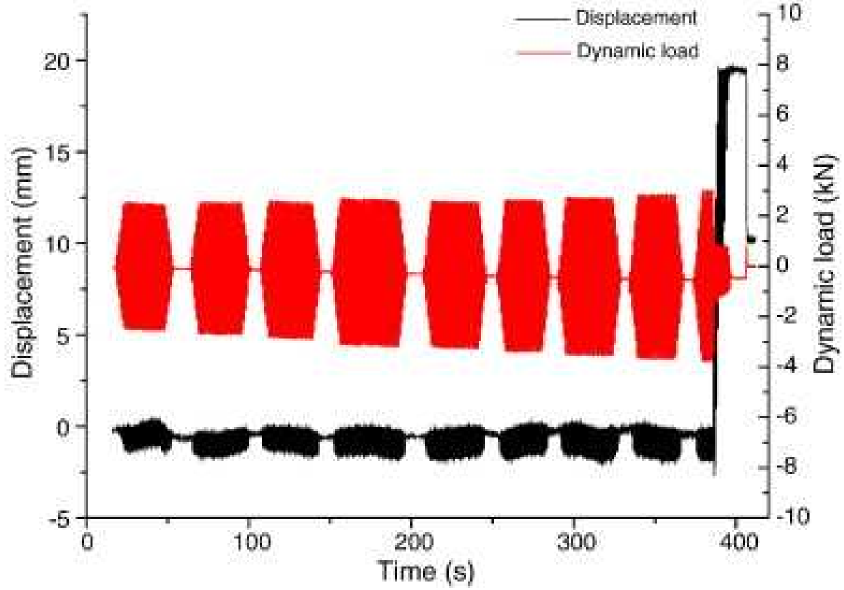
Computer logger



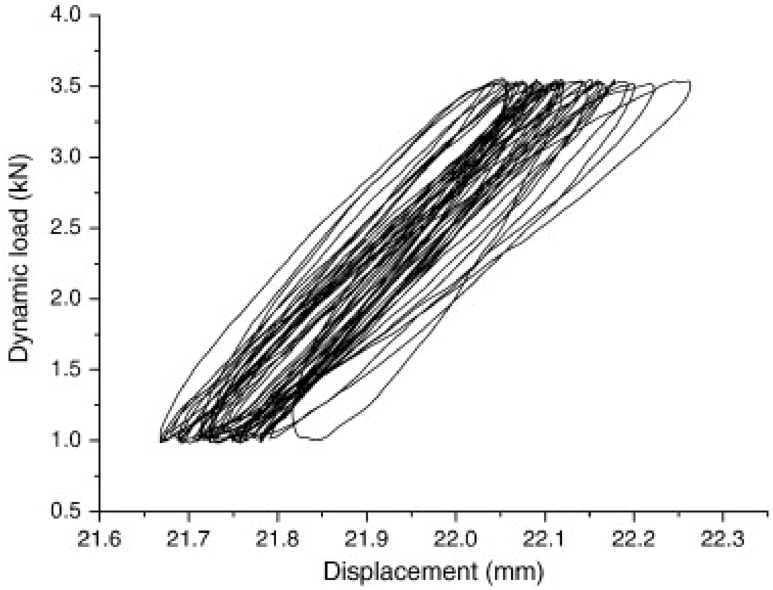
Temperature Sensor



Dynamic direct shear test —— Validation



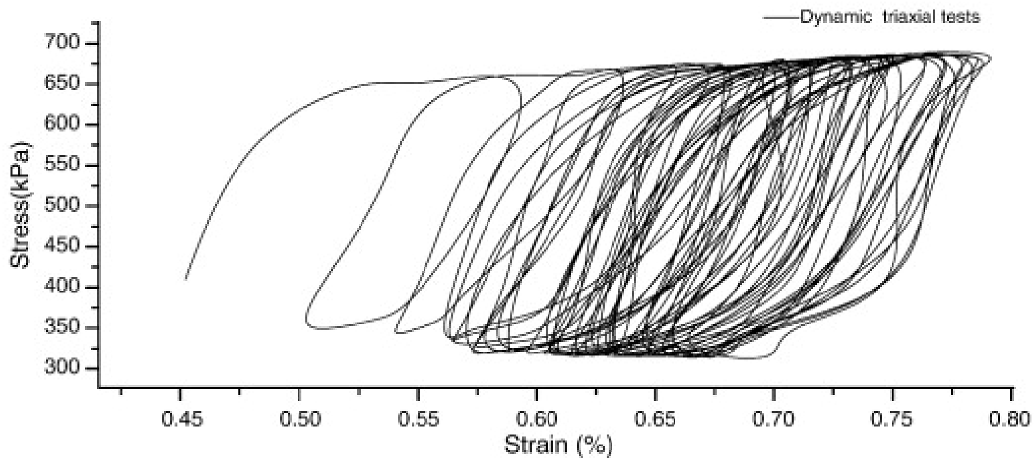
Displacement and dynamic load curve of a typical loading process

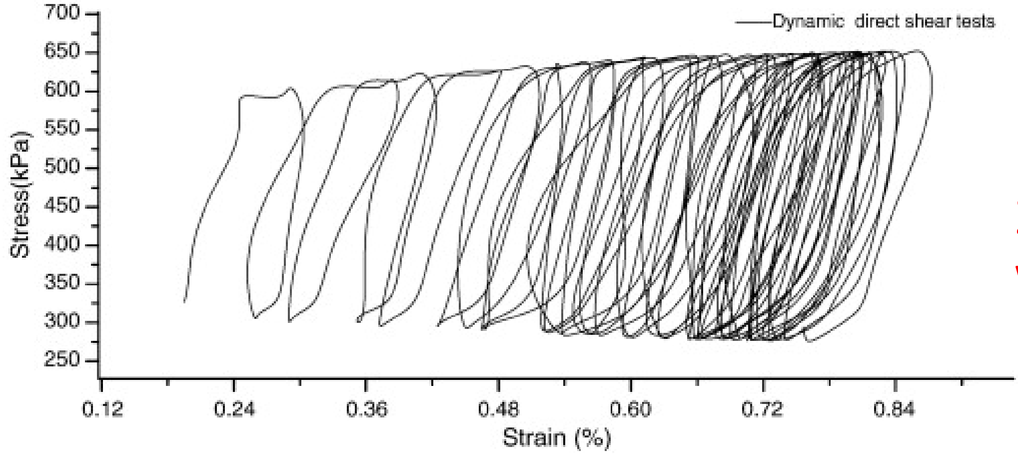


One level load–displacement hysteresis curve

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

Dynamic direct shear test ——
Compared with the dynamic triaxial apparatus





Comparison of hysteresis curve in two tests

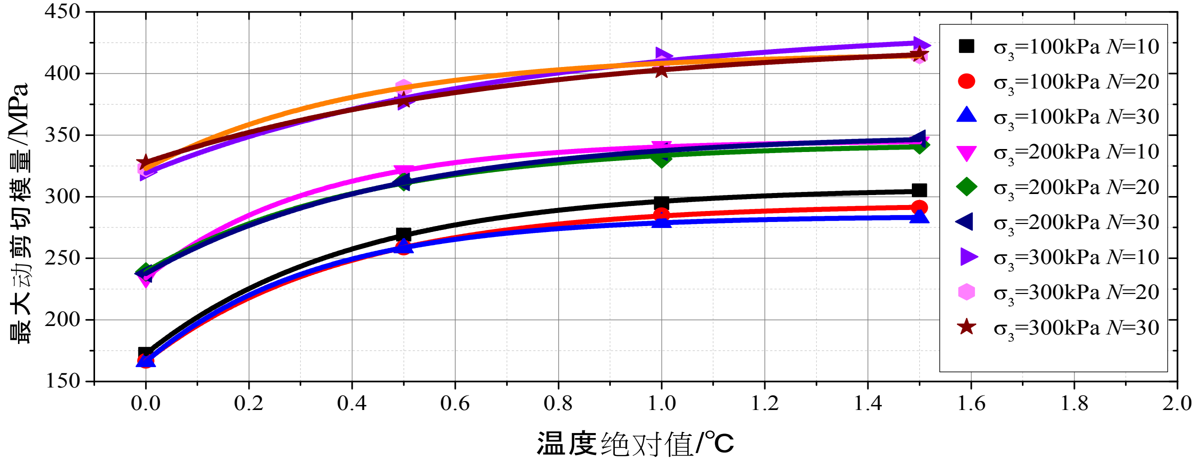
2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

Comparison with Triaxial Tests

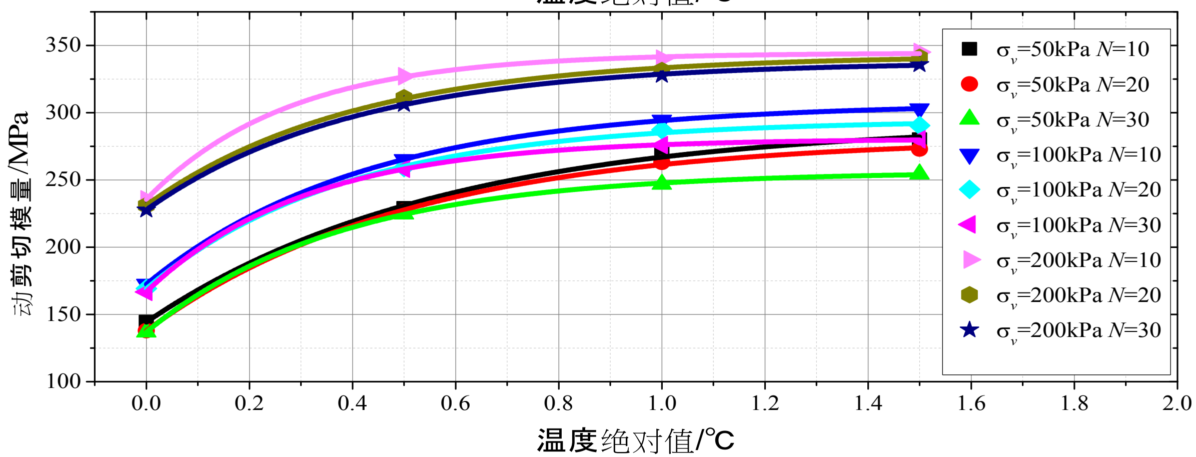
- Modulus of Frozen Soil
- Damping Ratio of Frozen Soil

Dynamic modulus —— Influenced by Temperature

Temperature controlled Dynamic triaxial test



Temperature Controlled Dynamic Direct shear test



$$G_{\mathrm{dmax}} = A_1 \cdot \exp(-|T_c|/B_1) + G_{\mathrm{d0}}$$

Dynamic modulus —— Influenced by Temperature

$$G_{dmax} = A_1 \cdot \exp(-|T_c|/B_1) + G_{d0}$$

σ_3=100kpa

$N = 30$

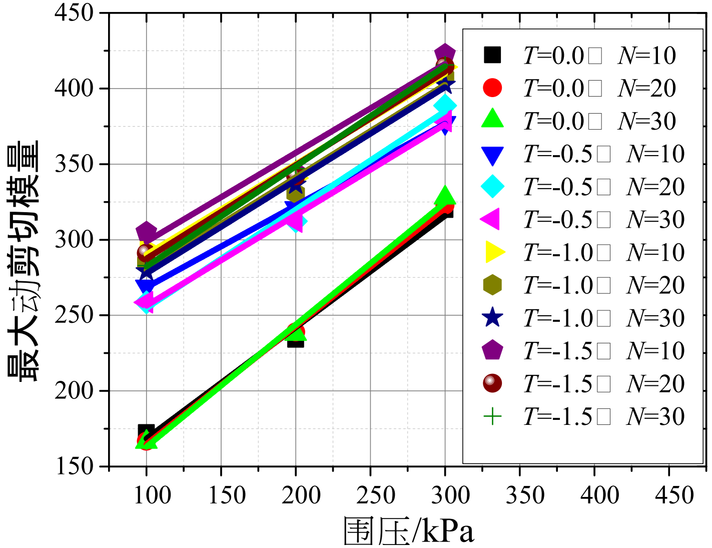
Temperature controlled Dynamic triaxial test

$$\left.\begin{aligned} G_{dmax} &= -118.303\exp\left(-|T_c|/0.328\right) + 284.184 \\ R^2 &= 0.9901 \end{aligned}\right\}$$

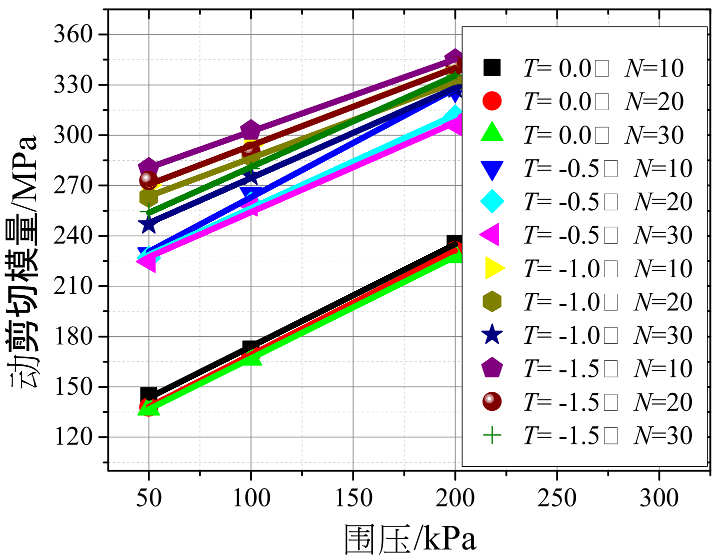
Temperature Controlled Dynamic Direct shear test

$$\left.\begin{aligned} G_{dmax} &= -113.873\exp\left(-|T_c|/0.308\right) + 265.653 \\ R^2 &= 0.9974 \end{aligned}\right\}$$

Dynamic modulus ——Influenced by Confining pressure



Dynamic triaxial test



Direct shear test

T_c= -1.0℃ $N = 20$

$$G_{\mathrm{dmax}} = 218.461 + 0.613\sigma$$

$$G_{\mathrm{dmax}} = 241.053 + 0.453\sigma$$

Dynamic modulus —— Influenced by Moisture content

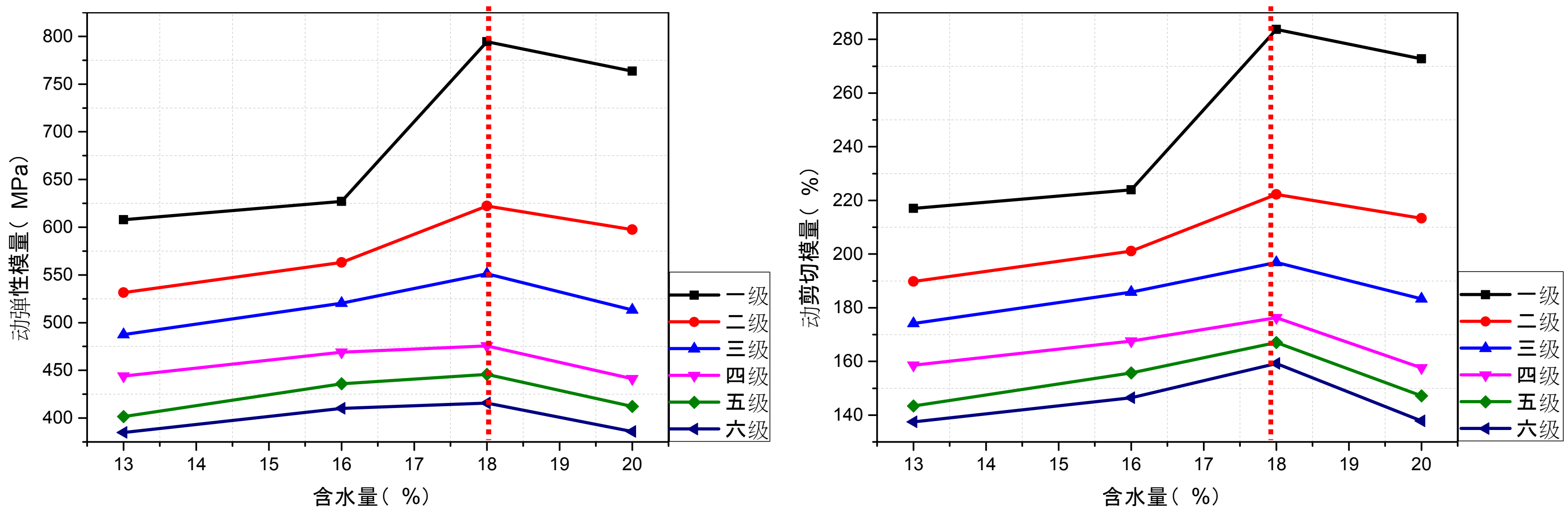
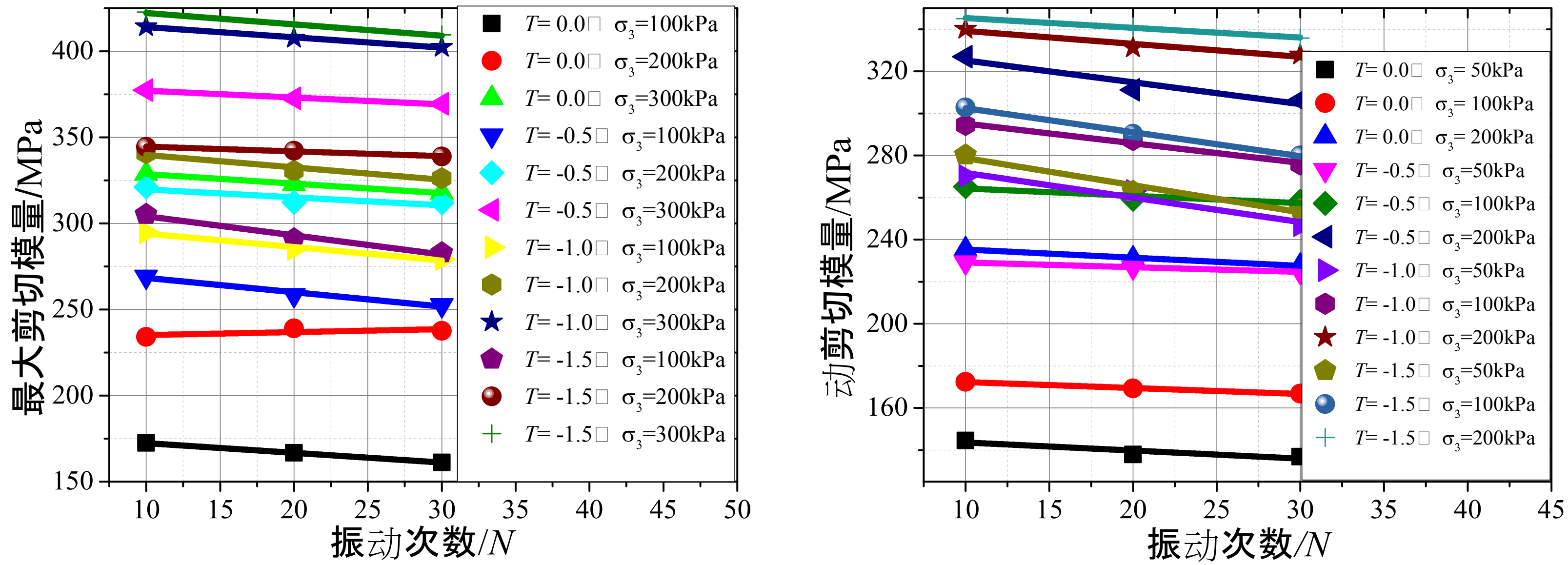


Fig. Relationship between dynamic modulus and different water content

Test parameters	Dynamic tri-axial test	Dynamic direct shear
Temperature(℃)	-1.5	-1.5
Confining pressure(Mpa)	0.5	0.5
Moisture content(%)	**13, 16, 18, 20**	**13, 16, 18, 20**
Vibration frequencies(Hz)	1	1

Dynamic modulus —— Influenced by Loading Cycles

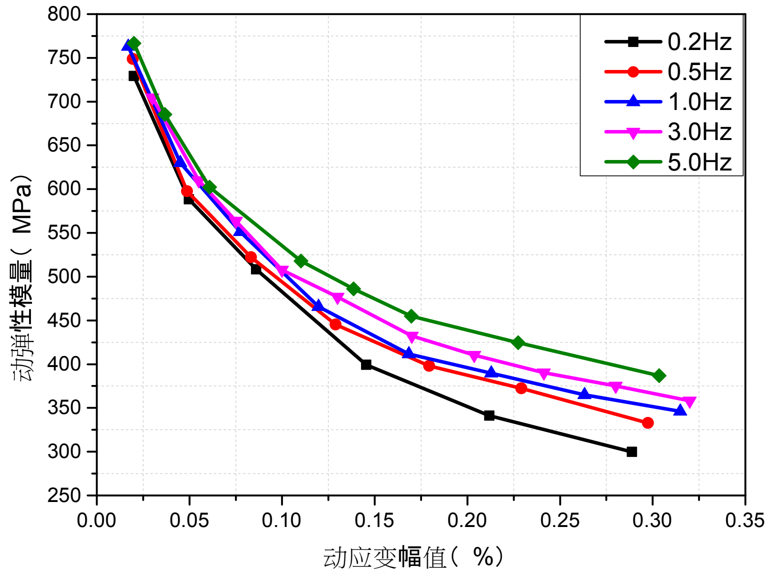


dynamic triaxial | dynamic direct shear

Fig. Reference shear strain vs. vibration times curve

$$G_{\mathrm{dmax}} = G_0 + G_1 N$$

Dynamic modulus —— Influenced by Frequencies



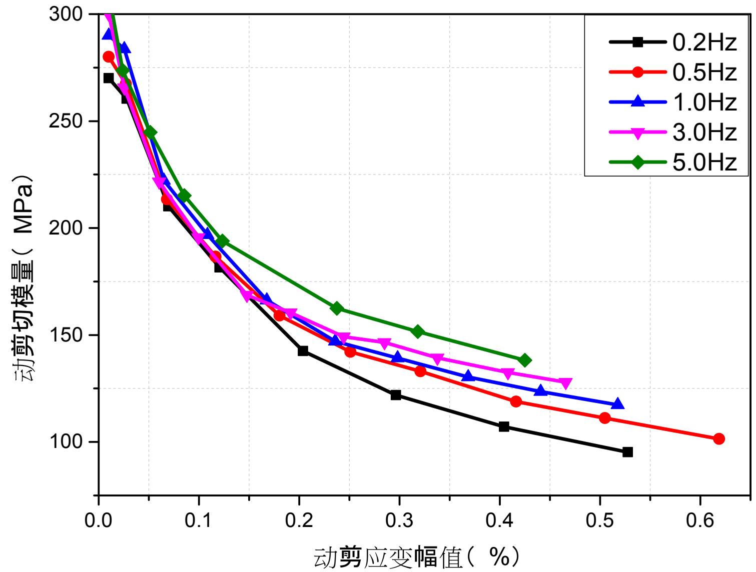


Fig. Relationship between dynamic elastic modulus and dynamic strain amplitude with different vibration frequencies

Test parameters	Dynamic tri-axial test	Dynamic direct shear
Temperature(℃)	-1.5	-1.5
Confining pressure(Mpa)	0.5	0.5
Moisture content(%)	18	18
Vibration frequencies(Hz)	**0.2, 0.5, 1.0, 3.0, 5.0**	**0.2, 0.5, 1.0, 3.0, 5.0**

Dynamic modulus —— A function of Temperrature, Confining pressure and load cycles

$$G_{\text{dmax}} = f(T_c, \sigma_3, N)$$

Temperature Controlled Dynamic triaxial test

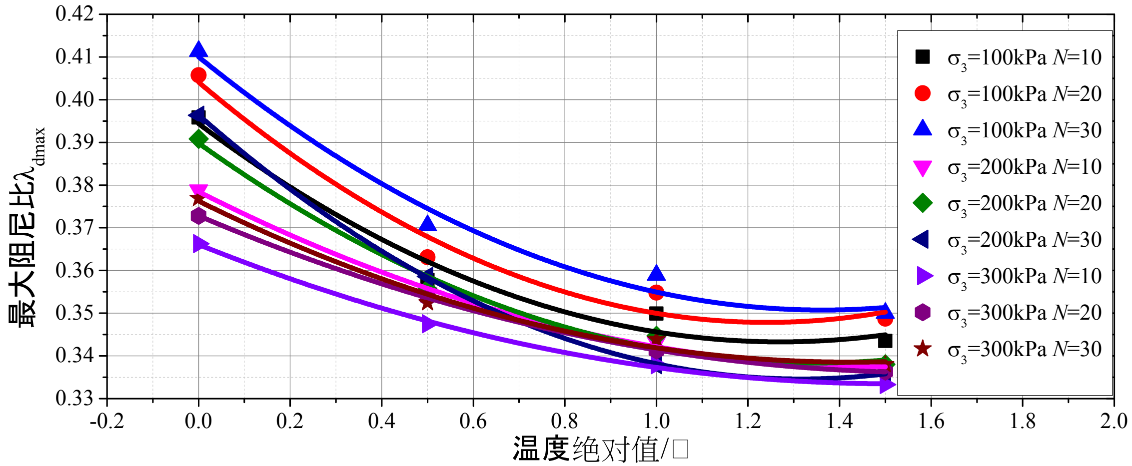
$$\left.\begin{aligned} G_{\text{dmax}} &= 142.21 + 187.42T_c - 63.81T_c^2 \\ &+ 49.46\left(\frac{\sigma_3}{100}\right) - 1.98\left(\frac{\sigma_3}{100}\right)^2 - 6.47\left(\frac{N}{10}\right) \\ R^2 &= 0.9852 \end{aligned}\right\}$$

Temperrature Controlled Dynamic Direct shear test

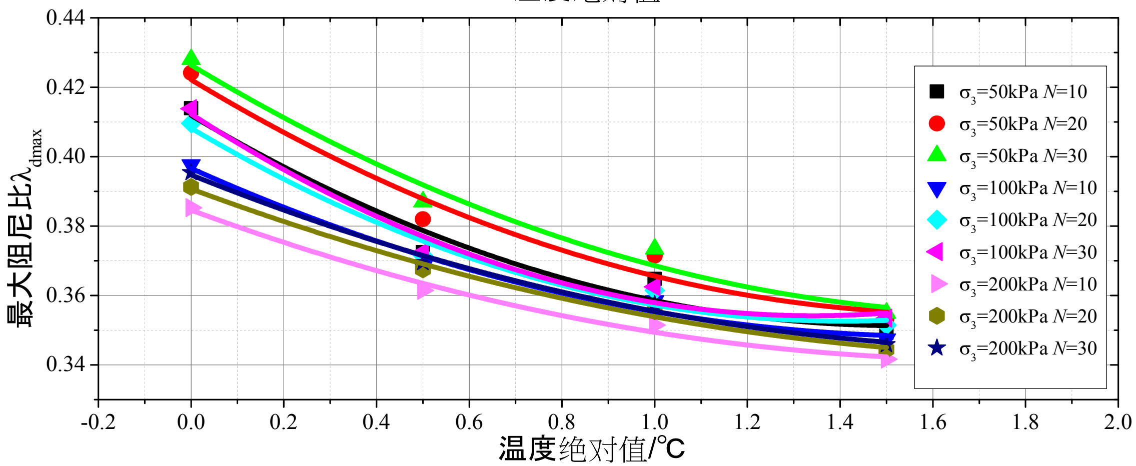
$$\left.\begin{aligned} G_{\text{dmax}} &= 133.07 + 195.75T_c - 79.95T_c^2 \\ &+ 58.18\left(\frac{\sigma_v}{100}\right) - 1.66\left(\frac{\sigma_v}{100}\right)^2 - 7.31\left(\frac{N}{10}\right) \\ R^2 &= 0.9827 \end{aligned}\right\}$$

Damping ratio —— Temperature

Dynamic triaxial test



Direct shear test



$$\lambda_{\mathrm{dmax}} = \lambda_1 + \lambda_2 \cdot |T_c| + \lambda_3 \cdot |T_c|^2$$

Damping ratio —— A function of Temperature, Confining pressure and load cycles

$$\lambda_{\mathrm{dmax}} = f(T_c, \sigma_3, N)$$

Dynamic triaxial test

$$\left.\begin{aligned}\lambda_{\mathrm{dmax}} &= 0.3948 - 0.06074T_c + 0.0174T_c^2 \\ &- 0.0089\left(\frac{\sigma_3}{100}\right) + 0.00019\left(\frac{\sigma_3}{100}\right)^2 + 0.00429N \\ R^2 &= 0.9708\end{aligned}\right\}$$

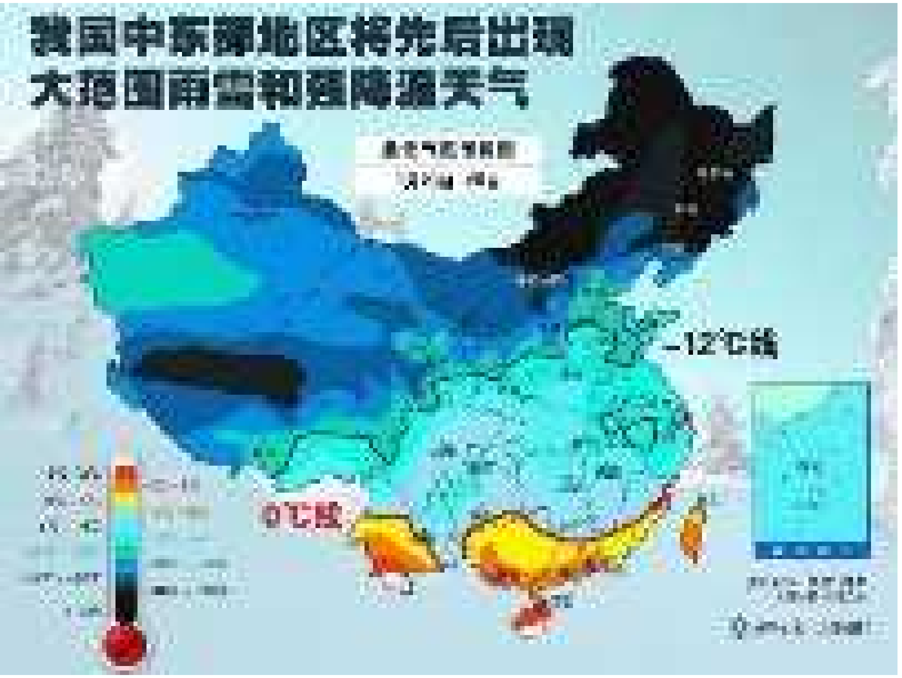
Direct shear test

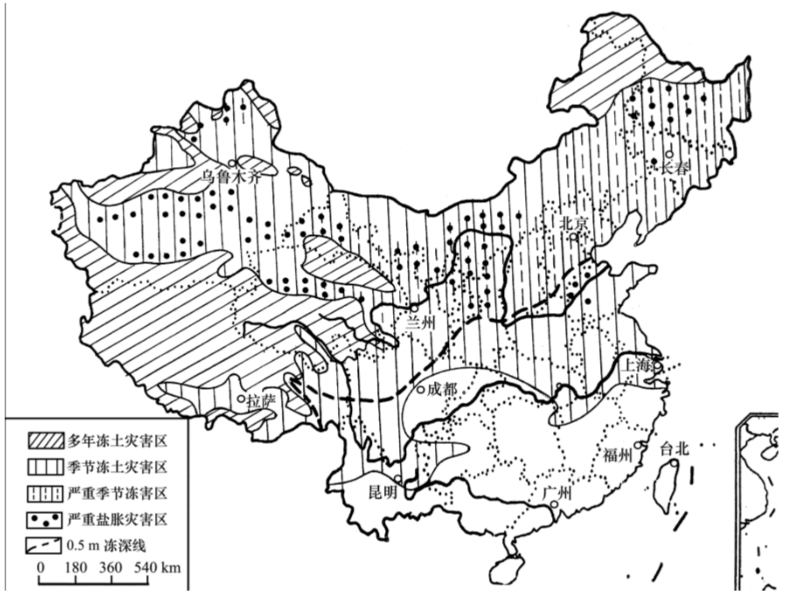
$$\left.\begin{aligned}\lambda_{\mathrm{dmax}} &= 0.4156 - 0.06744T_c + 0.02078T_c^2 \\ &- 0.00744\left(\frac{\sigma_3}{100}\right) + 0.005667\left(\frac{\sigma_3}{100}\right)^2 + 0.004457N \\ R^2 &= 0.9838\end{aligned}\right\}$$

Frost Related Problems： Examples

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

Cold Regions

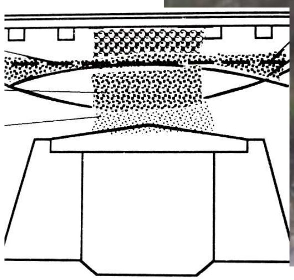




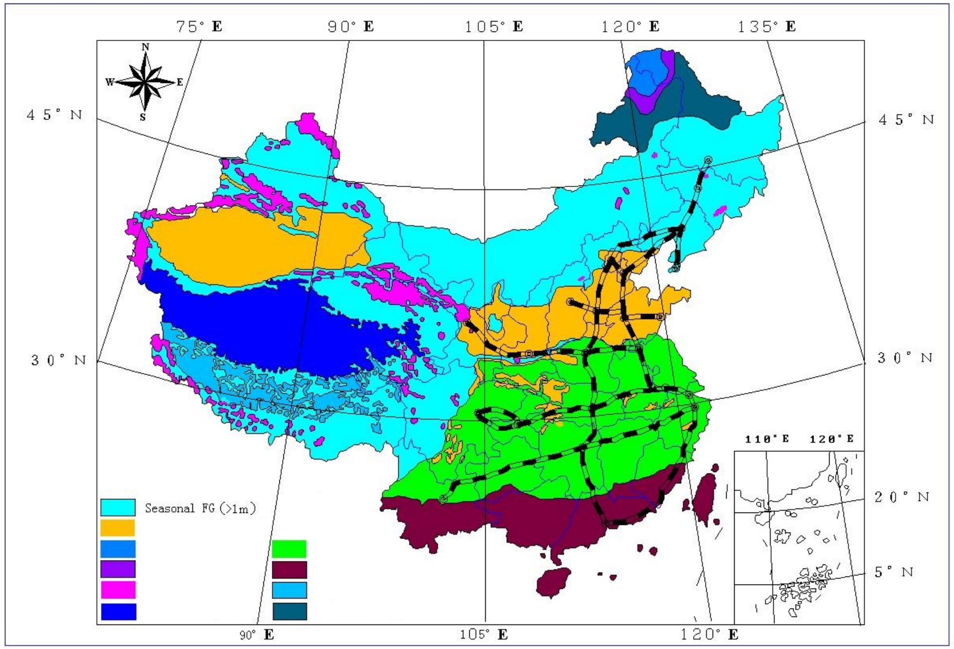
2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

(秦一沈,2000)

- The First High Speed Railway Experiment in China
- 200KM/h
- Ballast



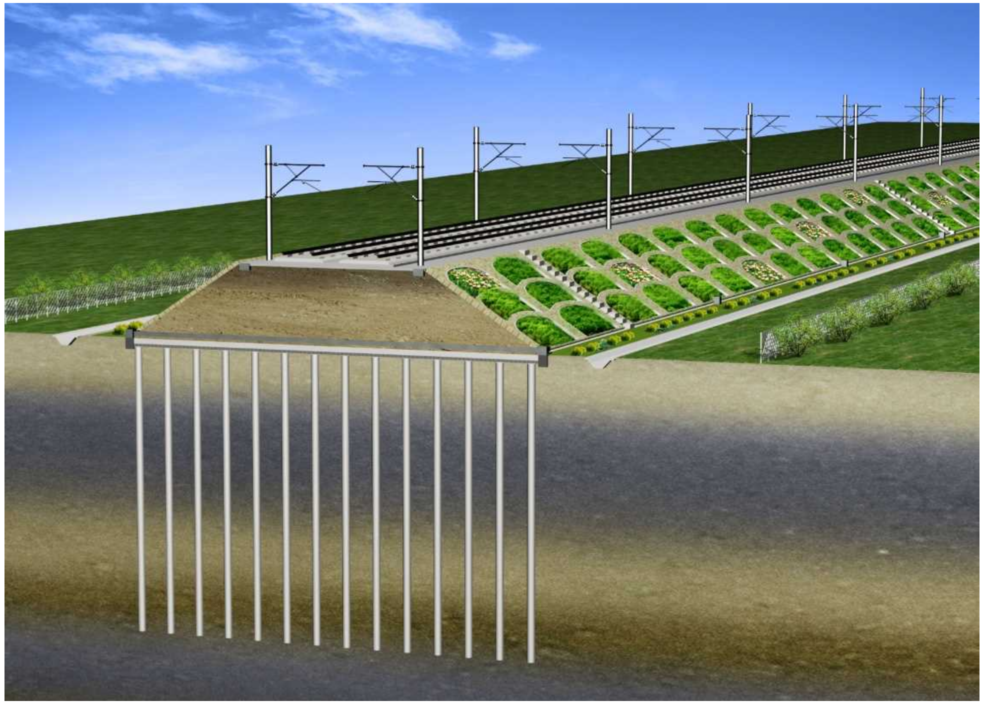
Harbin-Dalian HSR



Chinese frozen soil distribution and HSR plan

Designed Speed: 350KM/h
Slab Track- No Ballast
Average air Temp5.7℃,
Extrem high 38℃, low -36.5℃;
Freezing Depth170cm (Changchun)

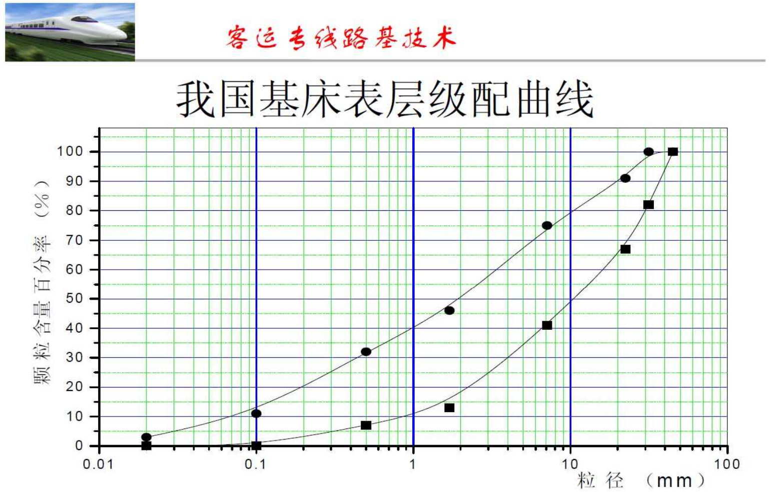
	Length/km	number	proportion
路基roadbed	231.245		25.58%
桥梁bridge	662.765	162	73. 32%
隧道tunnel	9.929	8	1.1%



Unfrost suseptable Fills Used

More Detailed Classification of Soil

Frost Suseptability. 5%, 15%, 30%



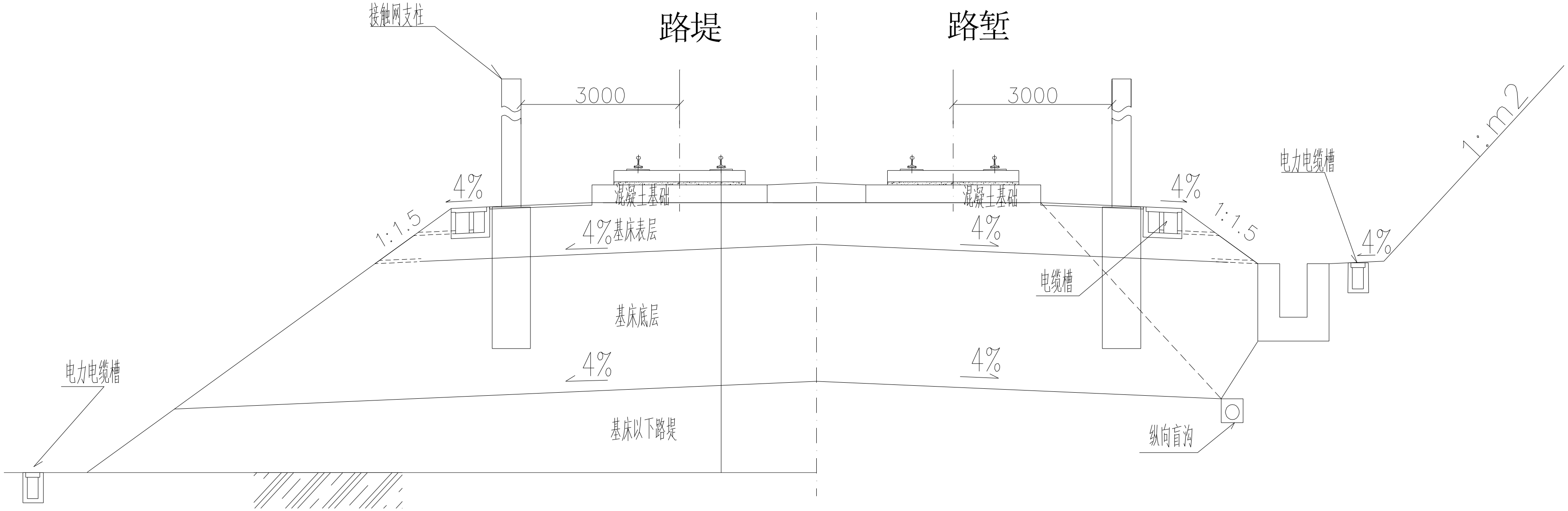
2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

北京交通大學 (原北方交通大学) Beijing Jiaotong University (Northern Jiaotong University)

Deformation source:

Subgrade, k, n, K30, Evd, Ev2

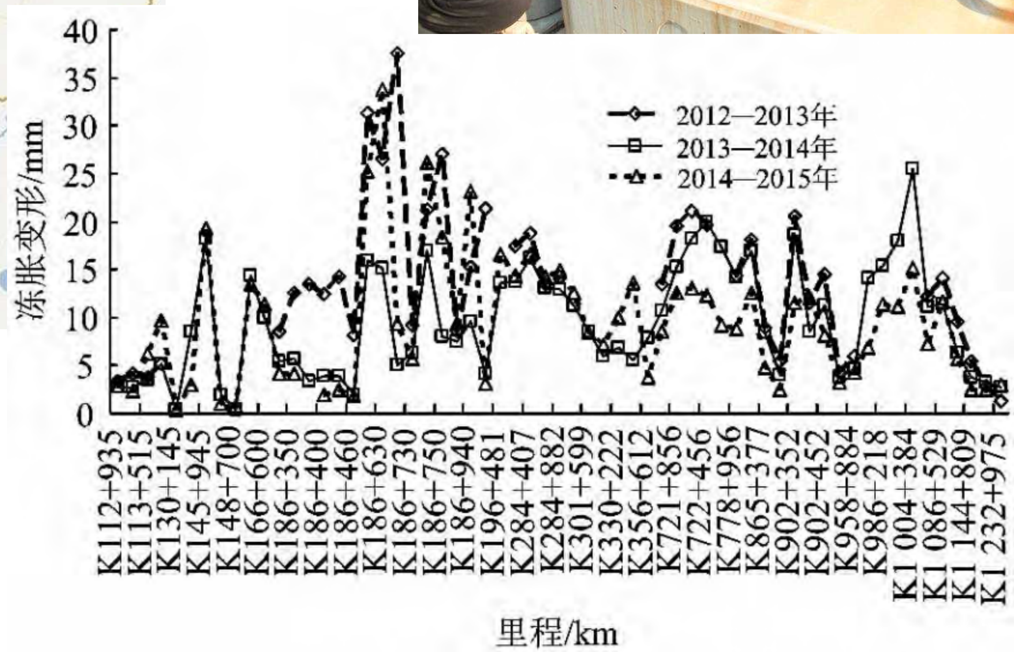
Base： Modification



2nd Japan-China Mini Workshop on High Speed Railway Geotechnics

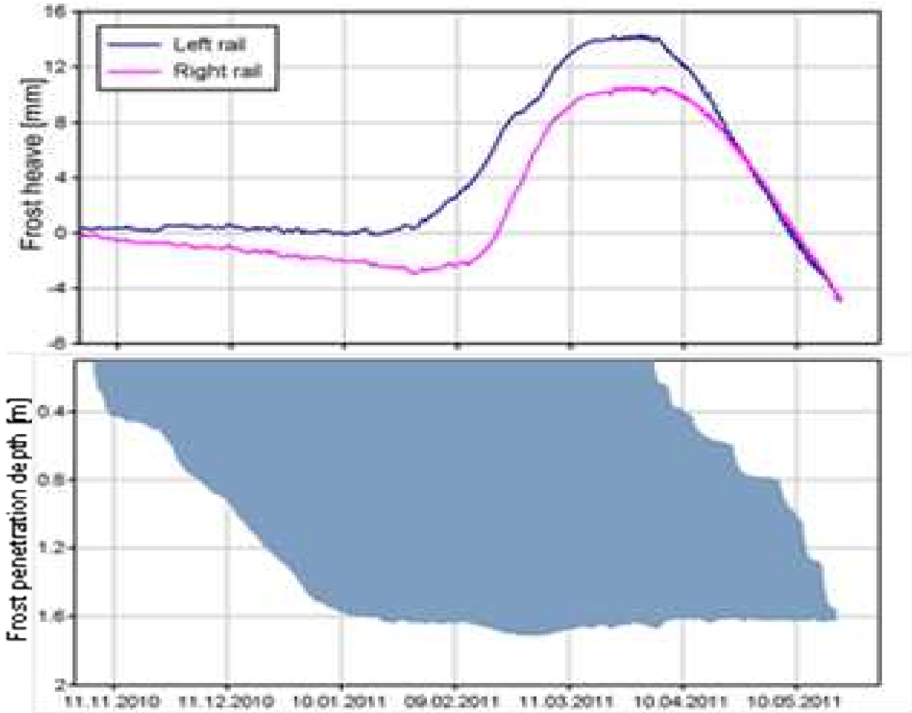
北京交通大學 （原北方交通大学）
Beijing Jiaotong University
(Northern Jiaotong University)

Harbin-Dalian high-speed railway

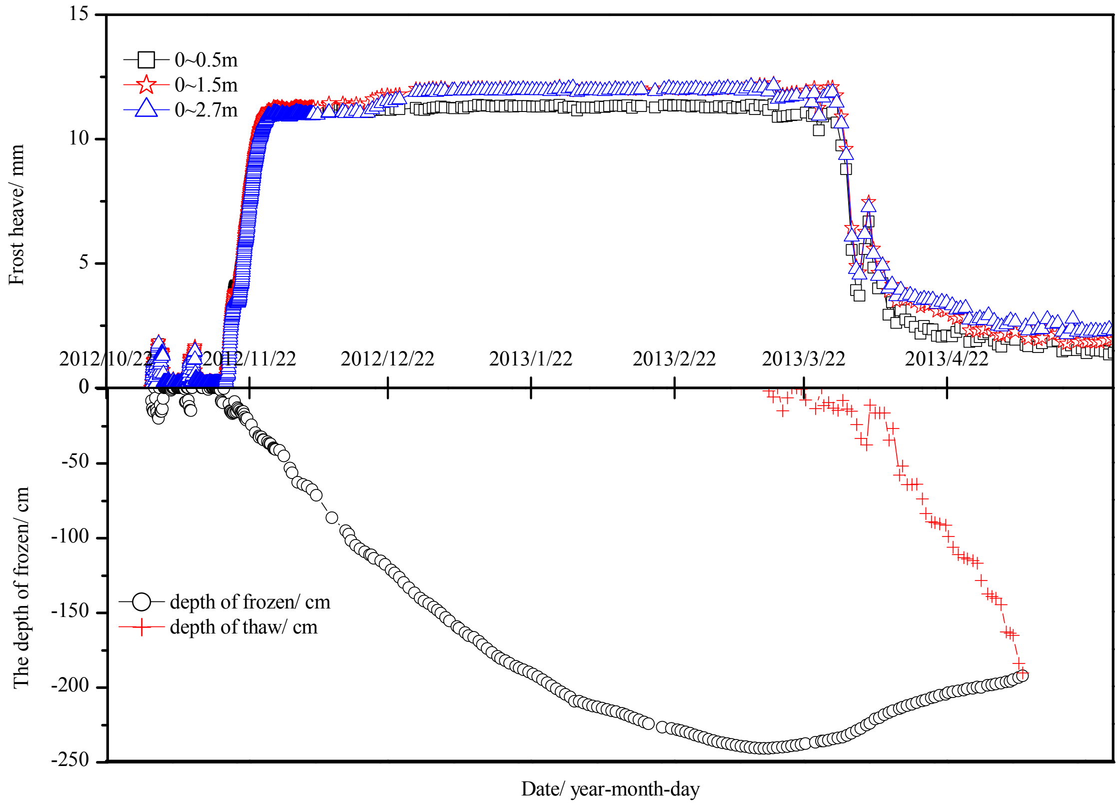


Maximum frost heave deformation

2nd Japan-China Mini Workshop on High Speed Railway Geotechnics



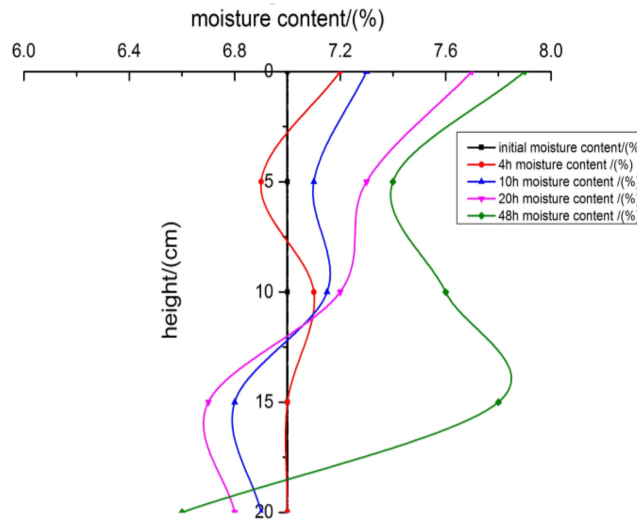
After Normikoula, 2013



After Niu 2014

北京交通大學 （原北方交通大学） Beijing Jiaotong University (Northern Jiaotong University)

试验	试验详情				冻胀量（mm）	冻结深度（cm）	冻胀率（%）
	含水率（%）	细颗粒（%）	冷端温度（°C）	压实度			
1	5	3	-5	0，90	0，65	9，56	0，68
2	5	5	-7	0，93	1，14	12，67	0，90
3	5	7	-10	0，97	0，67	18，61	0，36
4	7	3	-7	0，97	1，8	13，15	1，37
5	7	5	-10	0，90	1，83	17，42	1，05
6	7	7	-5	0，93	1，54	11，09	1，39
7	10	3	-10	0，93	1，38	17，25	0，8
8	10	5	-5	0，97	1，87	10，17	1，84
9	10	7	-7	0，90	1，47	12，91	1，14



水分迁移

Summary

- Lime-Cement Modified Soil for HSR
- Fiber Reinforced Soil has lower thermal conductivity, higher strength, longer durability
- Dynamic Shearing Box developed

- Thanks to National 973 project and NSCF!
- Thanks to my team members!