Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)

Cite this as: Yu-hao WU, Yan-hao FENG, Li-wu FAN, Qing WANG, Xin SONG, Zi-tao YU, 2022. Effects of moisture content and dry bulk density on the thermal conductivity of compacted backfill soil. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 23(8):610-620.
https://doi.org/10.1631/jzus.A2100673

Effects of moisture content and dry bulk density on the thermal conductivity of compacted backfill soil

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Key words:
Backfill soil; Compaction; Thermal conductivity; Moisture content; Dry bulk density

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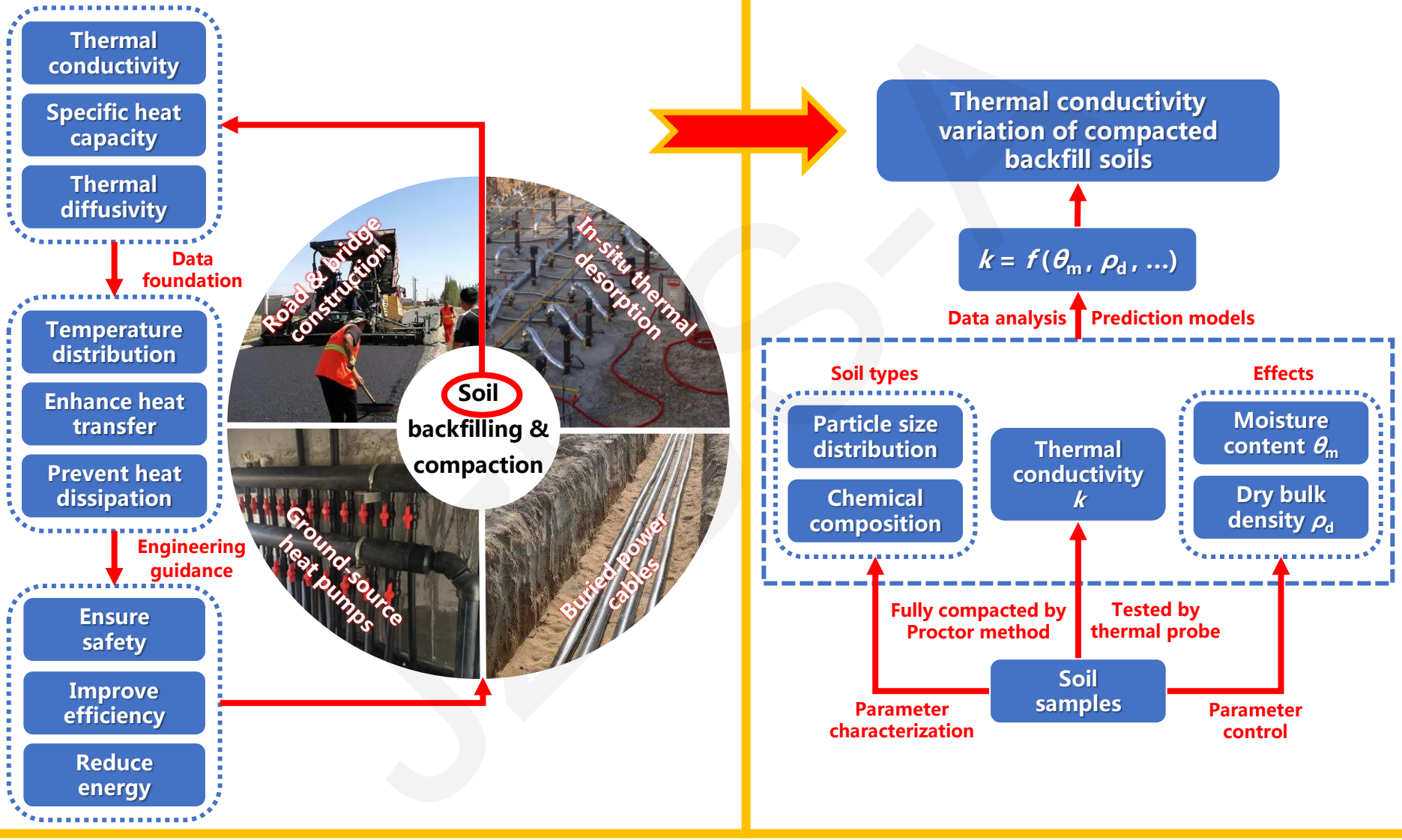
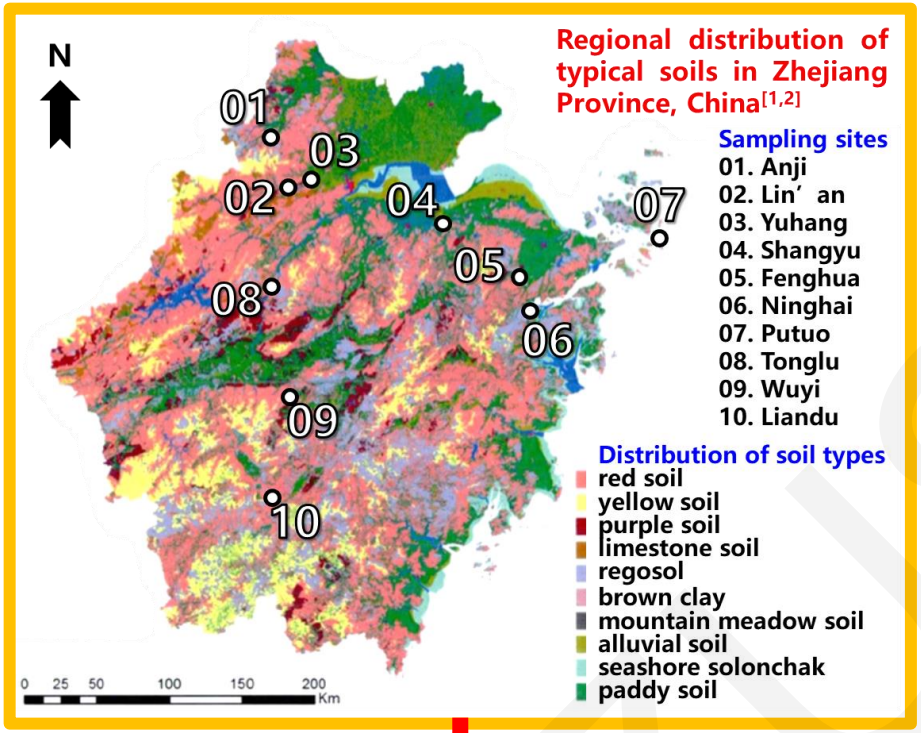
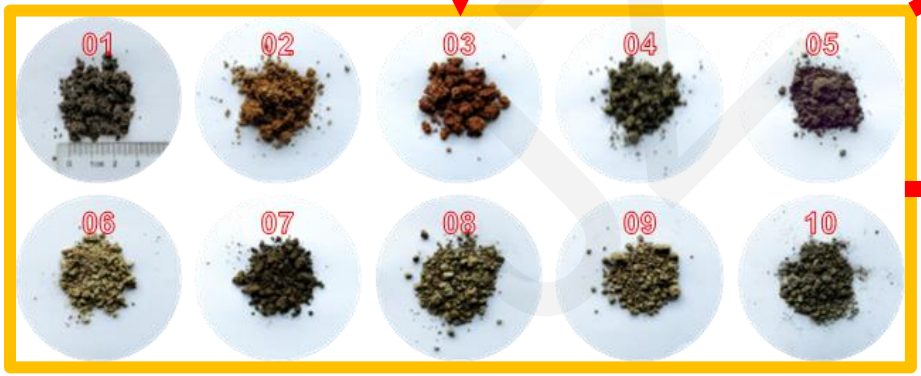
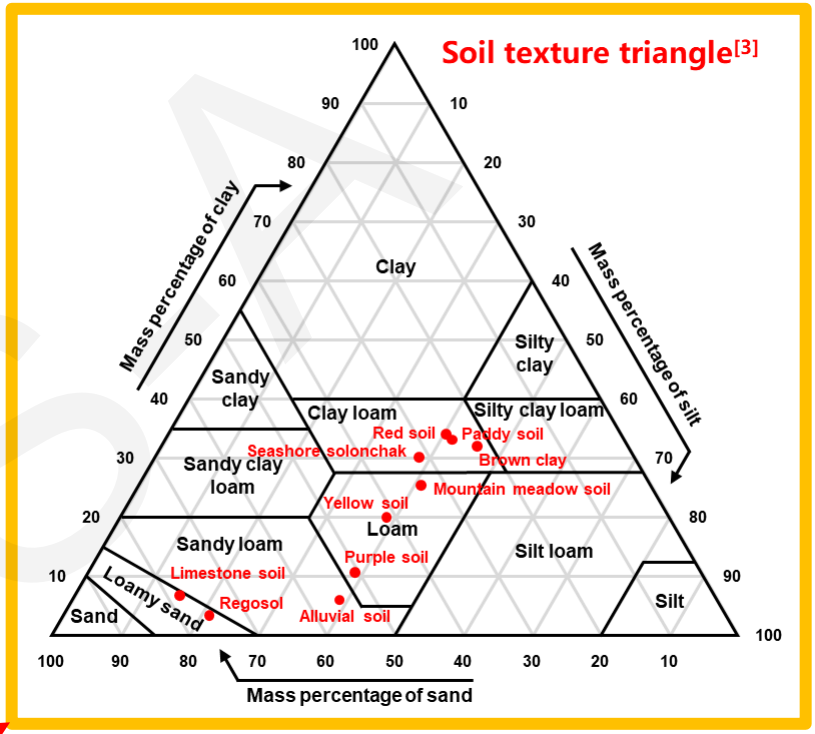
Background & methods



Soil sampling & characterization





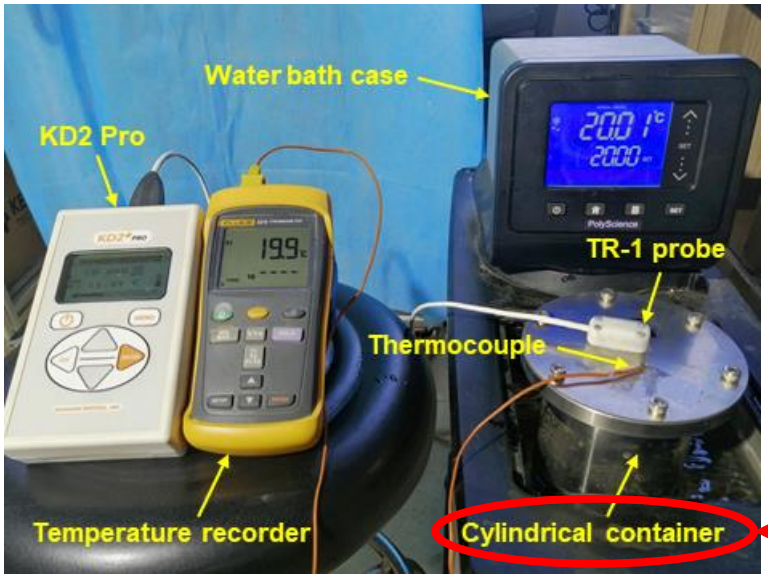


Chemical composition of soil samples

Soil type	Mass percentage (%)		
	Quartz	Other minerals*	Organic matters
Regosol	65.2	26.9	7.9
Paddy soil	81.4	13.4	5.2
Red soil	73.0	23.8	3.2
Alluvial soil	60.9	31.8	7.3
Purple soil	57.2	22.6	20.2
Seashore solonchak	63.0	29.6	7.4
Brown clay	52.7	40.6	6.7
Limestone soil	66.9	19.6	13.5
Yellow soil	29.6	67.0	3.4
Mountain meadow soil	67.7	19.4	12.9

[1] SMSS (Standard Map Service System), 2019. Citing Electronic Sources of Information. Ministry of Natural Resources of the People's Republic of China.
[2] Wu JP, Jing CW, Zhi JJ, 2014. Soil Geographic Database of Zhejiang Province and Its Application. Zhejiang University Press, Hangzhou, China, p.1-221 (in Chinese).
[3] USDANRCS (United States Department of Agriculture Natural Resources Conservation Service), 2017. Citing Electronic Sources of Information. United States Department of Agriculture.

Experimental conditions, apparatus & procedure



Experiment conditions (parameters of soil samples)

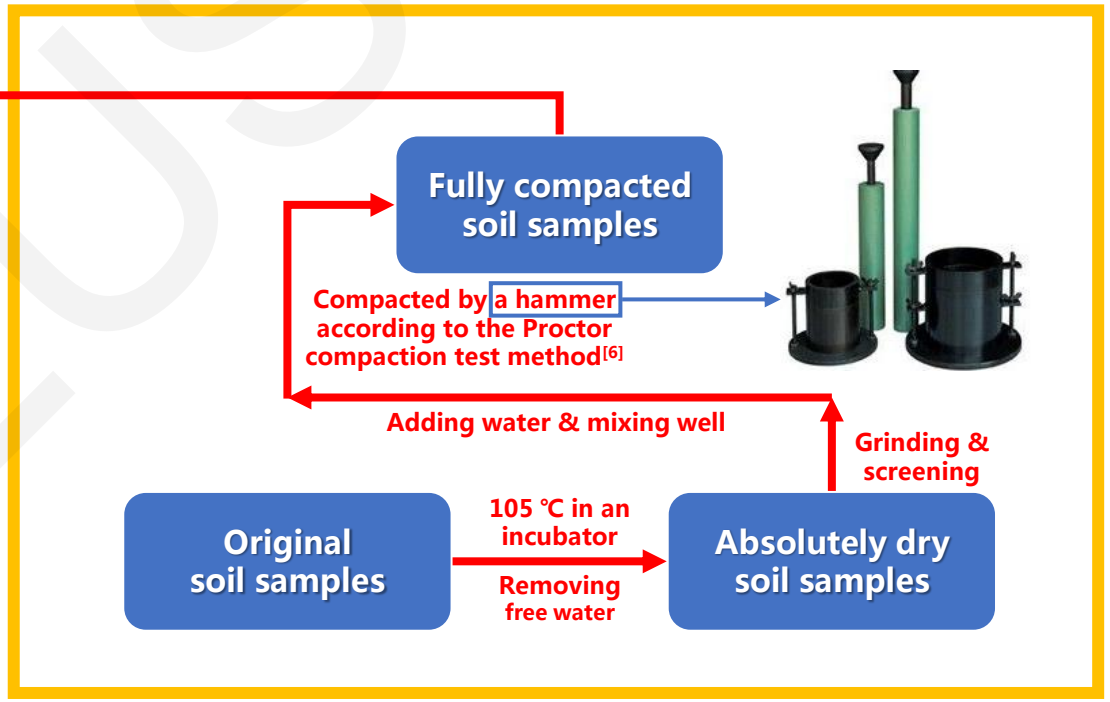
Parameter	Range	Reason / reference
Temperature	20 ℃	The annual average temperature of the soil at the superficial layer in east China is around 20 ℃[4]
Moisture content	0~25%	The moisture content of the soil at the superficial layer in east China is no more than 25% in most cases[5]
Relative compaction degree	100%	To simulate the fully compacted state of backfill soil in practical engineering

Decagon KD2 Pro thermal properties analyzer

- Theory: thermal probe method
- Equation: $k = [q \ln(\tau_2/\tau_1)]/[4\pi(T_2 - T_1)]$
- q-heating power, τ-time, T-temperature

TR-1 probe

- Material: stainless steel
- Diameter: 0.24 cm
- Length: 10 cm
- Range & accuracy: 0.1~4 W·m^{-1}·K^{-1} (±10%)
- Applicability: powder & porous material



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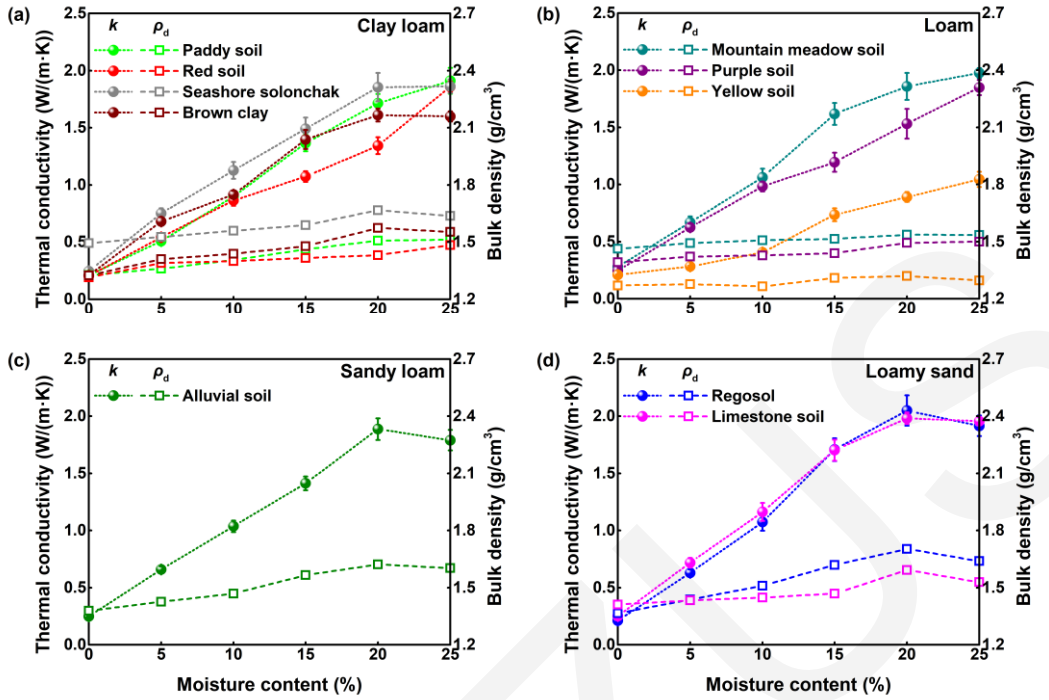
[4] Yu WJ, 2017. Study on soil temperature characteristics and annual average soil temperature estimation methods in China. MS Thesis, Shenyang Agricultural University, Shenyang, China (in Chinese).
[5] Ma GZ, Wei HL, Fu CB, 2000. Relationship between regional soil moisture variation and climatic variability over east China. Acta Meteorologica Sinica, 58(3):278-287. (in Chinese)
[6] MOHURD, AQSIQ, 2019. Standard for Geotechnical Testing Method, GB/T 50123-2019. National Standards of the People's Republic of China.

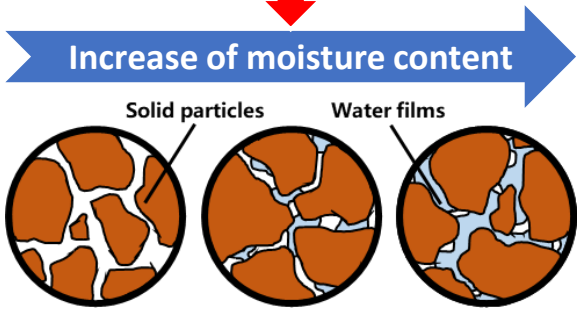
Results & discussion



Curves of dry bulk density and thermal conductivity to moisture content of soils with different textures

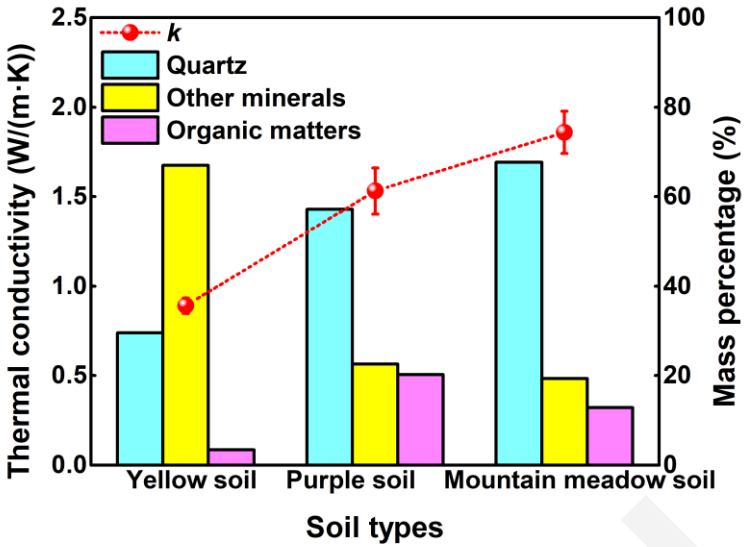
- The two curves (ρ_d & k) of sandy loam and loamy sand both increase with the increase in θ_m from 0% to 20% and decrease with the increase from 20% to 25%.
- The k curves of regosol and limestone soil almost coincide.
- The consistency for the two curves of clay loam and loam is poor.
- The two curves of paddy soil and red soil still increase when θ_m exceeds 20%, while those of seashore solonchak and brown clay decrease or remain nearly unchanged.

- k & ρ: solid phase (soil particles) > liquid phase (water) > gas phase (air)
- An appropriate amount of water can reduce soil pores and make the solid particles arrange more tightly.
- When the θ_m exceeds the critical value, the spacing of soil particles increases instead because a lot of the volume is occupied by the water films, which cause a decrease in ρ_d & k.



Schematic of solid & liquid phase in soils

Results & discussion



Effects of chemical composition on soil thermal conductivity (moisture content: 20%)

- Among all the soil minerals, the *k* of quartz is 7.69 W/(m·K), and that of other minerals is in a range of 1.53~5.51 W/(m·K) [7].
- Soil organic matters are mainly humus with an average *k* of about 1.26 W/(m·K) [8].
- Therefore, the increase in quartz generally has a positive effect on the increase in the *k* of soils.

- Due to the complex composition of soils, it is difficult to predict the *k* of all types of soils with any single formula accurately.
- It is necessary to propose different prediction formulae for different soil types.

Prediction formulae for two categories of fully compacted soils based on binary linear regression analysis

Soil texture	Prediction formula	P-value of regression coefficient			R^2
		$\theta_m^{1/2}$	$\rho_d^{1/2}$	Intercept	
Clay loam & loam	$k = 2.821\ \theta_m^{1/2} + 3.773\ \rho_d^{1/2} - 4.342$	6.54×10^{-15}	8.88×10^{-4}	1.08×10^{-3}	0.930
Sandy loam & loamy sand	$k = 2.718\ \theta_m^{1/2} + 4.958\ \rho_d^{1/2} - 5.698$	2.46×10^{-5}	2.00×10^{-2}	2.16×10^{-2}	0.942

[7] Xiao HL, Wu XJ, Zhou JH, 2007. Study on the calculation of thermal conductivity of rock and soil material. Subgrade Engineering, (3): 54-56 (in Chinese).
[8] Huang CY, Xu JM, 2010. Soil Science, 3rd Edition. China Agricultural Press, Beijing, China, p.1-379 (in Chinese).

Conclusions

- Overall, the maximum thermal conductivity of the ten typical soils in fully compacted state in this study is about 20~50% higher than that of the soils in natural or uncompacted state reported by others.
- With the increase in moisture content, the dry bulk density and the thermal conductivity of compacted backfill soils first increase rapidly and then slow down. When moisture content exceeding the critical value, dry bulk density and thermal conductivity remain unchanged basically or decrease slowly.
- The critical moisture content of soils with large particle size is usually lower than that of small particle size.
- The variation of the thermal conductivity with moisture content for compacted backfill soils with the same texture classification is similar.
- Soil thermal conductivity is positively correlated with quartz content, which is extremely obvious when there is a great discrepancy in quartz content.