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以氣象站數據建立營建工地熱暴露評估即時校正模式之研究

A Study on the Development of a Real-time Correction Model for
Assessing Construction Site Heat Exposures Using the
Meteorological Data

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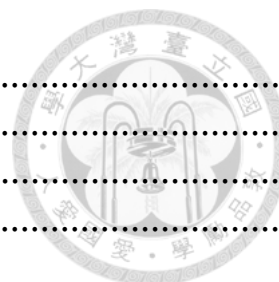
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中文摘要



本研究旨在建立一套將氣象站數據轉化為營建工地綜合溫度熱指數 (WBGT) 之即時校正模式。近年因氣候變遷與氣溫持續升高，戶外作業族群面臨更高的熱壓力暴露風險。其中營造業因長時間曝曬與高體力勞動，熱傷害發生率遠高於其他產業，長期暴露不僅會引發中暑等急性疾病，更與慢性腎臟病等長期健康損害有顯著關聯。

然而，現行預警機制普遍存在雙重局限：首先在指標代表性上，多數指引僅採用涵蓋氣溫與濕度的熱指數 (HI)，無法全面反映風速與輻射對人體熱平衡的綜合影響；其次在空間代表性上，直接以氣象站的觀測值代表工地現場，亦忽略了施工現地因材料蓄熱與通風受阻所造成的局部氣候落差。這兩大問題，導致營建工地的現場熱風險遭到嚴重低估。

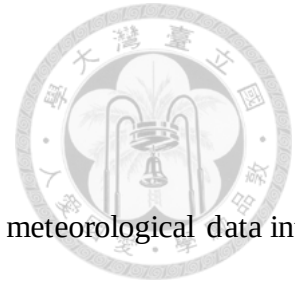
本研究採取物理模型轉換與現場實測校正之混合式策略。首先，整合工地現場儀器量測資料與中央氣象署鄰近測站數據，比較工地現場之 HI、氣象站之 HI，以及工地現場之 WBGT、氣象站推估之 WBGT 之差異。接著，本研究採取兩階段校正策略：首先透過 Liljegren 物理能量平衡模型，結合工地經緯度與時序參數，計算出氣象站推估之 WBGT，並進一步以現場實測資料建立迴歸校正式，使氣象站推估結果更貼近營建工地現場之實際熱暴露情形。

研究結果顯示，工地現場之 HI 較氣象站之 HI 約高 2°C ，且兩者在熱危害分級上呈現明顯差異；氣象站之 HI 多集中於第 1 至第 2 級，而工地現場之 HI 則主要落於第 3 級。WBGT 分析亦顯示，工地現場之 WBGT 較氣象站推估之 WBGT 約高 1°C ，雖然兩者觀察值範圍相近，但此差距已足以使部分資料落入較高風險分級。統計分析顯示，HI 與 WBGT 在氣象站資料與工地現場資料之間皆具有顯著差異 ($p < 0.05$)，說明僅依賴氣象站資料可能造成熱危害風險低估，證實現地校正之必要性。

在模型建立方面，Liljegren 物理模型推估之氣象站推估 WBGT 與工地現場之 WBGT 具有高度相關性 ($R^2=0.9524$)，顯示其具備良好的預測潛力。然而，模型仍存在約 1°C 之低估誤差，可能影響熱危害分級判斷。因此，本研究進一步導入現地校正機制，並將此兩階段架構建置為 Excel 即時估計工具，以提升氣象站資料應用於營建工地熱危害管理之準確性與實務可行性。

關鍵字：營建工地、職業熱暴露、綜合溫度熱指數 (WBGT)、氣象資料、微氣候、Liljegren 物理模型、現地校正

Abstract



This study aims to develop a real-time correction model that converts meteorological data into the Wet Bulb Globe Temperature (WBGT) specific to construction sites. Due to climate change and continuously rising temperatures in recent years, outdoor worker populations face higher risks of heat stress exposure. Among these, the construction industry suffers from a significantly higher incidence of heat injury than other industries due to prolonged sun exposure and high physical labor. Prolonged exposure not only triggers acute diseases such as heat stroke but also correlates significantly with long-term health damage such as chronic kidney disease.

However, existing early-warning mechanisms generally suffer from dual limitations. First, in terms of index representativeness, guidelines in Taiwan only adopt the Heat Index (HI), which covers temperature and humidity, failing to comprehensively reflect the combined effects of wind speed and radiation on human thermal balance. Second, in terms of spatial representativeness, directly using weather station observations to represent construction sites also overlooks the local climate gaps caused by material heat retention and obstructed ventilation at the construction sites. These two major problems lead to a severe underestimation of the onsite heat risks at construction sites.

This study adopted a hybrid strategy combining physical model conversion with field-based correction. Field measurements from a construction site were integrated with meteorological data from a nearby Central Weather Administration station to compare differences between construction-site HI and weather-station HI, as well as construction-site WBGT and weather-station-estimated WBGT. The Liljegren physical energy balance model was then applied to estimate weather-station-estimated WBGT using weather station data, site-specific geographic

coordinates, and temporal parameters. A regression-based correction equation was further developed using field measurements to adjust the weather-station-estimated WBGT toward the actual thermal exposure conditions at the construction site.



The results showed that construction-site HI was approximately 2°C higher than weather-station HI, resulting in clear differences in heat hazard classification. Weather-station HI values were mainly distributed in Categories 1 and 2, whereas construction-site HI values were predominantly classified as Category 3. WBGT analysis also showed that construction-site WBGT was approximately 1°C higher than weather-station-estimated WBGT. Although the observed ranges of the two WBGT datasets were comparable, this difference was sufficient to shift part of the results into a higher risk category. Statistical analyses confirmed significant differences between construction-site and weather-station values for both HI and WBGT ($p < 0.05$), indicating that reliance solely on weather station data may underestimate heat hazard risks at construction sites.

For model development, the weather-station-estimated WBGT derived using the Liljegren physical model showed a strong correlation with construction-site WBGT ($R^2 = 0.9524$), demonstrating its strong predictive potential. However, an underestimation of approximately 1°C remained, which may affect heat hazard classification. Therefore, this study further incorporated field-based correction and implemented the two-stage framework into an Excel-based real-time estimation tool to improve the accuracy and practical applicability of weather station data for construction site heat hazard management.

Keywords: Construction site, occupational heat exposure, wet bulb globe temperature (WBGT), meteorological data, microclimate, Liljegren's model, on-site correction

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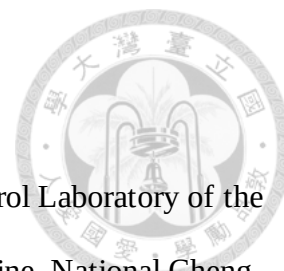
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Chapter 1 Introduction



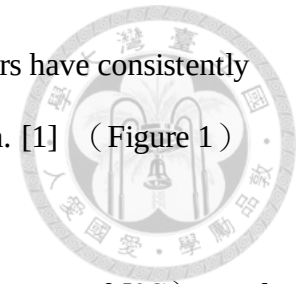
This practicum was conducted at the Exposure Assessment and Control Laboratory of the Department of Environmental and Occupational Health, College of Medicine, National Cheng Kung University. The laboratory primarily focuses on the identification, assessment, and control of workplace and environmental hazards, combining environmental monitoring, exposure assessment, engineering controls, and statistical models to investigate the impacts of chemical and physical hazards on worker health. In recent years, the laboratory has also emphasized exposure model estimation and long-term exposure assessment, transforming limited field measurement data into exposure information applicable to occupational health management through model construction.

This study aims to develop a real-time correction model that converts meteorological data into the WBGT specific to construction sites, which aligns with the internship unit's expertise in exposure assessment, physical hazard analysis, and model construction. Through the methodological training and research resources acquired during the practicum process, this study was able to further contrast the differences between meteorological data and onsite heat exposures at construction sites, and to develop a correction model with practical application potential, thereby enhancing the spatial representativeness and operational feasibility of heat hazard management.

1.1 Recent Trends in Anomalous High Temperatures

Due to the convergence of a subtropical island climate and the urban heat island effect, Taiwan's annual average temperature and the number of high-temperature days have demonstrated an upward trend in recent years. According to the *Annual Climate Report 2024* published by the Central Weather Administration, the annual average temperature in Taiwan in 2024 reached 24.6°C, which is 0.7°C higher than the 1991–2020 climatological norm of 23.9°C, making it the highest on

record. Furthermore, the annual average temperatures over the past 10 years have consistently exceeded past climatological norms, illustrating a distinct warming pattern. [1] (Figure 1)



If the number of high-temperature days (e.g., daily maximum temperature $\geq 35^{\circ}\text{C}$) is utilized as a measure of "anomalous high temperature" to reflect the increasing frequency of heatwaves and heat advisories, it becomes evident that outdoor worker populations will face a higher thermal stress exposure load and greater thermal strain under identical operational patterns. (Figure 2)

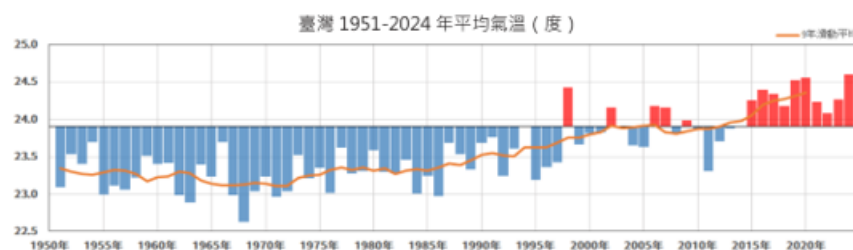


Figure 1 Interannual variation of average temperature in Taiwan, 1951–2024 [1].

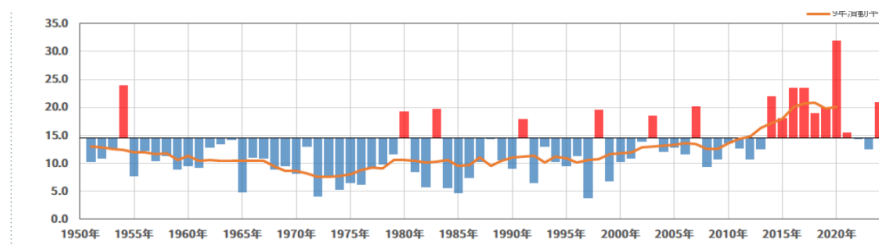
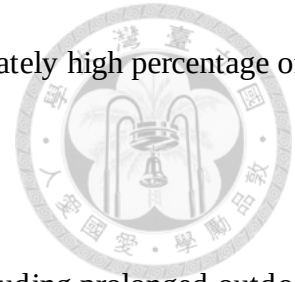


Figure 2 Cumulative Number of High-Temperature Days ($\geq 35^{\circ}\text{C}$) and Daily Maximum Temperatures in Taiwan (1951–2024)

1.2 Current Status of Heat Hazards and Health Impacts in the Construction Industry

Due to its operational characteristics, the construction industry is widely recognized as one of the sectors most severely impacted by heat hazards. As described by Nowrouzi-Kia et al. in 2026, the incidence rates of heat-related illnesses and injuries among construction workers are substantially higher than those in other industries; even though the sector does not account for the

largest proportion of the total labor force, it still represents a disproportionately high percentage of heat-related fatalities [2].



Construction sites present multiple risk factors for heat exposure, including prolonged outdoor exposure to direct sunlight, high humidity, poor ventilation, and high-intensity physical workloads [3]. Furthermore, the personal protective equipment (PPE) that workers are required to wear often impedes sweat evaporation and heat dissipation, further exacerbating the physiological thermal load. Government agencies have also pointed out an upward trend in occupational disasters related to heat hazards in recent years. Over the past five years, a cumulative total of 10 fatal occupational disasters caused by high temperatures occurred during outdoor operations across Taiwan, with the construction industry accounting for a high proportion of these cases [4].

In terms of health impacts, thermal stress not only causes acute illnesses such as heat exhaustion and heat stroke, but chronic, repeated exposure to high-temperature environments is also significantly associated with systemic health impairments, such as chronic kidney disease (CKD) [5]. Beyond the health dimension, thermal stress exerts a negative impact on productivity. Empirical research from Hong Kong indicates that for every 1°C increase in WBGT, direct work time (DWT) decreases by an average of approximately 0.33% [6]. Moreover, under high-heat exposure, the degradation of cognitive function and decision-making capabilities, triggered by the elevation of core body temperature, skin temperature, and heart rate, will directly increase the risks of postural instability and occupational safety accidents during operations [7].

1.3 Regulatory Standards, Management Methods, and Existing Issues for Anomalous High Temperatures

To protect the health of workers engaged in outdoor operations under high temperatures and to prevent heat injuries, the "Guidelines for the Prevention of Heat Hazards for Workers in High-Temperature Outdoor Operations", by referencing the risk tiering and management measures of the U.S. Heat Index (HI), was promulgated by the Occupational Safety and Health Administration, Ministry of Labor, Taiwan (Taiwan OSHA) [8]. These guidelines require employers to proactively consult the meteorological data (e.g., air temperature and relative humidity) issued by the nearby weather station operated by the Central Weather Administration before conducting operations, and utilize the Heat Index classification table to determine the heat hazard risk level and corresponding risk management measures (Table 1). Additionally, employers can also simultaneously utilize the "High-Temperature Outdoor Operation Heat Hazard Prevention Mobile Information Network" developed by the Taiwan OSHA to grasp the daily heat index, serving as a basis for assessing outdoor heat hazard risks and implementing management measures.

Table 1 Heat index chart and heat hazard risk classification table.

Air Temperature (°C)	43.3	level4																			
	42.2	57.8																			
	41.1	54.4	58.3																		
	40.0	51.1	54.4	58.3																	
	38.9	48.3	51.1	55.0	58.3																
	37.8	45.6	48.3	51.1	53.9	57.8															
	36.7	42.8	45.6	48.3	50.6	53.3	56.7														
	35.6	40.6	42.8	45.0	47.2	49.4	52.2	55.6	58.9												
	34.4	38.3	40.0	42.2	44.4	46.7	49.4	51.1	53.9	57.2											
	33.3	36.1	37.8	39.4	41.1	43.3	45.6	48.3	51.1	53.9	57.2										
	32.2	34.4	35.6	37.2	38.3	40.6	42.2	44.4	46.7	49.4	52.2	55.0	58.3								
	31.1	32.8	33.9	35.0	36.1	37.8	39.4	40.6	42.8	45.0	47.2	50.0	52.8	55.6							
	30.0	31.1	31.7	32.8	33.9	35.0	36.7	37.8	39.4	41.1	43.3	45.0	47.2	49.4							
	28.9	29.4	30.6	31.1	31.7	32.8	33.9	35.0	36.1	37.8	38.9	40.6	42.2	44.4							
	27.8	28.3	28.9	29.4	30.0	31.1	31.7	32.2	33.3	34.4	35.6	36.7	37.8	39.4							
	26.7	27.2	27.8	28.3	28.9	29.4	30.0	31.1	31.7	32.2	32.8	33.9	35.0								
		26.7	26.7	27.2	27.2	27.8	27.8	28.3	28.9	28.9	29.4	30.0	30.0	30.6							
		40	45	50	55	60	65	70	75	80	85	90	95	100							
		Relative humidity (%)																			

Wet Bulb Globe	T_{nwb} , T_g , T_a	High	Workplaces /
Temperature (WBGT)			Sports Fields



The current regulatory framework generally suffers from three distinct categories of limitations. First, there is a fundamental trade-off between "field measurability" and "physiological representativeness" regarding the chosen indices and thresholds. Second, many operational sites lack the resources for continuous measurement or specialized personnel for data interpretation, making it difficult to translate these indices into real-time decision-making. Third, even when meteorological warnings are utilized, systemic discrepancies frequently exist between regional weather station data and the microclimate of actual work sites due to factors such as shading, ground surface materials, localized wind fields, and radiation conditions. Without localized calibration, these discrepancies can lead to the underestimation or overestimation of risks, thereby compromising the effectiveness of control measures.

Regarding this gap, the Taiwan OSHA has also pointed out that the predicted values from the information network may not fully and accurately reflect the actual exposure to heat hazards in certain specialized environments. Consequently, it is recommended that while these predicted values can serve as an initial reference for general scenarios, on-site WBGT measurements remain necessary for validation.

As shown in Table 3, international regulations for outdoor or high-heat operations predominantly adopt WBGT as the core environmental thermal stress index. In contrast, current practice in Taiwan still relies heavily on the HI as the primary warning indicator. These measures function largely as advisory classifications and promotional tools, lacking a robust institutional

linkage to on-site work/rest schedules, clothing adjustments, and physiological monitoring protocols.

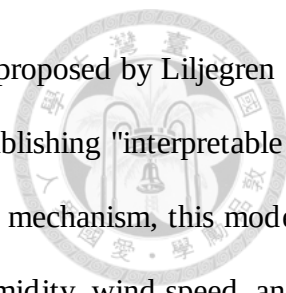


Table 3 Comparison of Heat Hazard Assessment Frameworks Across Countries and Organizations

Country / Organization	Primary Index	Regulatory Mandate
United States (ACGIH)	WBGT	Non-mandatory (Guidelines)
Japan (MHLW / Ministry of Health, Labour and Welfare)	WBGT	Legally Binding
European Union (EU-OSHA)	WBGT + PHS	Nationally Specified Regulations
Australia (SafeWork)	WBGT + Subjective Feedback	No Unified Legislation
Canada (Provinces)	WBGT	Decentralized Management
Taiwan (Ministry of Labor / ILOSH)	HI	Not Integrated into Regulations

1.4 Current Status and Challenges in Direct Conversion of Meteorological Data into Real-Time On-Site Control Indices

The direct conversion of Meteorological Data into real-time heat hazard indices for on-site control has become a major strategic direction worldwide in responding to high-temperature risks.



Among numerous estimation methods, the physical energy balance model proposed by Liljegren et al. in 2008 has been widely recognized as the benchmark approach for establishing "interpretable and portable" real-time control indices. Through a rigorous energy balance mechanism, this model utilizes parameters from the Weather Station—such as air temperature, humidity, wind speed, and solar radiation—to directly solve for natural wet-bulb temperature (T_{nwb}) and globe temperature (T_g), thereby calculating the Wet Bulb Globe Temperature (WBGT). Compared to empirical regression equations that rely solely on historical data, the Liljegren physical model possesses high physical consistency and cross-regional portability. Furthermore, its outputs are consistent with the standard definitions of WBGT specified in ISO 7243:2017[9] and ACGIH guidelines[10].

However, the practice of "directly inputting Weather Station observations into a physical model" still faces two critical challenges during practical implementation. The first is the data constraint of radiation parameters: if the Weather Station lacks crucial radiation variables, such as solar irradiance, alternative radiation proxies (such as cloud cover or sunshine duration) must be established to maintain the model's estimation accuracy. The second is the systematic bias caused by microclimates: while Weather Stations are typically located in open, standardized sites, construction zones frequently feature complex and dynamic operational conditions (such as scaffolding obstructing ventilation, bare ground surfaces, and the heat retention and re-radiation of concrete and steel structures), resulting in high spatial heterogeneity of the microclimate. Consequently, even when applying the rigorous Liljegren physical model, estimations derived purely from regional Weather Stations may still introduce systematic errors, making it difficult to fully represent the actual thermal load experienced by workers at specific operational points.

Chapter 2 Methods

This study adopts a hybrid strategy that combines "physical model conversion" with "on-site empirical calibration". Given our objective to balance model interpretability, ensure that the required inputs can be obtained from standard Weather Stations, and simultaneously estimate T_g and T_{nwb} to comply with the computational logic of ISO 7243, the energy balance method proposed by Liljegren is selected as the primary estimation framework. This framework is subsequently integrated with on-site measurement data from a Kestrel 5400FW for calibration, ultimately establishing a real-time index capable of long-term operation.

The specific research and application strategies can be summarized into three components:

1. **Data Processing:** Establishing a time-alignment workflow between the Weather Station and on-site measurements, while retaining and processing key variables that influence radiation and evaporation (such as wind speed height conversion and solar radiation features).

Wind speed measured at the reference height was converted to the target height using the power-law wind profile: $v = v_0 \left(\frac{h}{h_0} \right)^\alpha$

where v_0 is the wind speed measured at the reference height h_0 , h is the target height, and α is the wind profile exponent determined according to surface roughness.[11]

2. **Model Estimation:** Utilizing the Liljegren model to calculate T_{nwb} , T_g , and WBGT, and substituting alternative radiation proxies (such as sunshine duration, UVI, or shortwave radiation estimates) when necessary to compensate for missing radiation inputs from the Meteorological Data.
3. **Data Calibration:** Leveraging the field measurement data alongside the Meteorological Data to develop regression models, thereby enabling the Weather Station estimates to precisely reflect the microclimate discrepancies inherent to construction sites.

2.1 Research Field and On-Site Instrumentation

This study designated a construction site in southern Taiwan as the primary research field and utilized a Kestrel 5400FW Fire Weather Meter Pro WBGT (Kestrel Instruments, Nielsen-Kellerman, USA) to conduct heat stress measurements. (Figure 3). The measurement specifications of the instrument are as follows: the air temperature (T_a) range is from -29.0°C to 70.0°C with an accuracy of $\pm 0.5^{\circ}\text{C}$; the globe temperature (T_g) range is from -29.0°C to 60.0°C with an accuracy of $\pm 1.4^{\circ}\text{C}$; the relative humidity (RH) range is from 0% to 100% with an accuracy of $\pm 2.0\%$; the wind speed (U) range is from 0.6 m/s to 40.0 m/s with an accuracy of 3.0%; the natural wet-bulb temperature (T_{nwb}) depends on on-site temperature and humidity with an accuracy of $\pm 1.8^{\circ}\text{C}$; and the WBGT is determined by the on-site air temperature, globe temperature, and natural wet-bulb temperature with an accuracy of $\pm 0.7^{\circ}\text{C}$ (<https://reurl.cc/ZZEmN6>). The data sampling interval is set to one record per minute.

Field measurements were conducted on eight sampling days in 2025: July 19, 22, 30, and 31; August 2 and 28; and October 14 and 15. The sampling dates and measurement data were provided by the practicum site. Only periods identified as sunny based on field observations were included in the analysis.



Figure 3 Kestrel 5400FW Fire Weather Meter Pro WBGT

2.2 Meteorological Data

The meteorological data are primarily obtained from the hourly or high-time-resolution observation data from nearby Weather Stations operated by the Central Weather Administration. In this study, data from Yongkang Weather Station (station code: 467420) was used. The retrieved parameters include at least: air temperature (T_a) relative humidity (RH) or dew point temperature (T_d), wind speed (U), atmospheric pressure (P), and variables related to the radiation environment (such as global solar radiation, cloud cover, sunshine duration, or weather phenomenon codes).

Weather-station observations were available at 10-minute intervals. Sunny periods at the weather station were defined as hours with more than 0.5 hours of sunshine duration and global solar radiation exceeding 0.432 MJ/m^2 .

2.3 Heat Indices

This study designates WBGT as the core heat stress index. Its primary advantage lies in its widespread adoption across international occupational health standards and its direct integration with work-rest recommendations and operational management thresholds (ISO 7243:2017).

In addition, the Heat Index (HI) was used as a supplementary indicator of thermal exposure. HI is an empirical approximation of Steadman's apparent temperature and is primarily determined by air temperature and atmospheric moisture.[12] Although various HI algorithms have been proposed, Anderson et al. (2013) found that the National Weather Service (NWS) algorithm showed the closest overall agreement with Steadman's original apparent temperature values.[13] Therefore, the NWS-based algorithm was adopted in this study.

The WBGT and HI for both outdoor workplaces and weather stations are calculated using the following formulas:

1. **WBGT (outdoor):** $0.7 \times T_{nwb} + 0.2 \times T_g + 0.1 \times T_a$

Where:

T_{nwb} : Measured Natural wet-bulb temperature ($^{\circ}\text{C}$),



T_g : Measured Globe temperature ($^{\circ}\text{C}$),

T_a : Measured Air temperature ($^{\circ}\text{C}$).

2. **WBGT (Weather Stations)** : $0.7 \times T_{nwb} + 0.2 \times T_g + 0.1 \times T_a$

Where:

T_{nwb} : Liljegren model predicted Natural wet-bulb temperature ($^{\circ}\text{C}$),

T_g : Liljegren model predicted Globe temperature ($^{\circ}\text{C}$),

T_a : Weather Stations Air temperature ($^{\circ}\text{C}$).

3. **HI (outdoor and Weather Stations):**

$$c_1 + c_2 T_a + c_3 RH + c_4 T_a RH + c_5 T_a^2 + c_6 RH^2 + c_7 T_a^2 RH + c_8 T_a RH^2 + c_9 T_a^2 RH^2$$

Where:

T_a : Air temperature ($^{\circ}\text{C}$),

RH: Relative humidity (%),

c_1 - c_7 : c_1 : -42.38, c_2 : 2.049, c_3 : 10.14, c_4 : -0.2248, c_5 : -6.838×10^{-3} , c_6 : -5.484×10^{-2} , c_7 : 1.229×10^{-3} , c_8 : 8.528×10^{-4} , c_9 : 1.990×10^{-6} .

To evaluate the discrepancies in WBGT and HI between the construction site and the weather station, a paired-sample t-test was conducted, with statistical significance defined as $p < 0.05$.

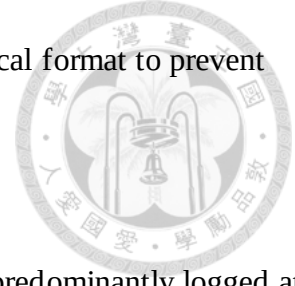
Additionally, box plots were utilized to analyze and compare the data distributions between the two setups.

2.4 Data Processing Workflow

To enhance the comparability between field measurements and weather station observations, a harmonization procedure for variables and units was executed during the data aggregation stage.

This process involved standardizing all temperature metrics to $^{\circ}\text{C}$, relative humidity to %, and wind

speed to m/s, alongside converting all time fields into a unified chronological format to prevent mismatching caused by instrumental clock drifts or format discrepancies.



In terms of temporal synchronization, whereas the on-site data were predominantly logged at a 1-minute interval, the weather station data were typically provided as 10-minute records. Consequently, this study adopted a pairing approach anchored to the weather station timestamps, aggregating the on-site data into 10-minute intervals to facilitate comparison across identical timescales. The representative value of the on-site data within each 10-minute window was determined using the median, thereby mitigating the confounding effects of extreme outliers induced by transient shading, instantaneous wind gusts, or localized operational interference.

2.5 Calibration Model Development for Weather Station Data

The objective of the calibration model in this study is to estimate heat stress indices for site-specific operations using conventional meteorological data from weather stations when on-site measurements are unavailable, thereby supporting operational management and early risk warning. The modeling strategy employs a two-stage approach.

2.5.1 Stage 1: Physical Conversion

The globe temperature T_g , and natural wet-bulb temperature T_{nwb} are first estimated from weather station data to calculate the station-side WBGT[14, 15].

1. Estimation of Field Globe Temperature (T_g) :

$$T_g^4 = \left(\frac{1}{2}\right) (1 + \varepsilon_a) T_a^4 - \left(\frac{h}{\varepsilon_g \sigma}\right) (T_g - T_a) + \left(\frac{SR}{2 \varepsilon_g \sigma}\right) (1 - \alpha_g) \left[1 + \left(\frac{1}{2 \cos \theta} - 1\right) f_{dir} + \alpha_{sfc}\right]$$

Table 4 Parameters Used in the Globe Temperature Calculation

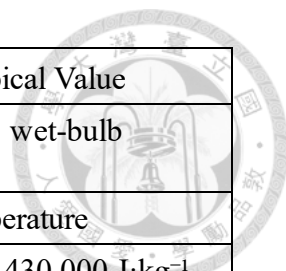
Symbol	Parameter	Unit	Description / Typical Value
T _g	Globe temperature	K	Estimated globe temperature
T _a	Air temperature	K	Ambient air temperature
ε _a	Atmospheric emissivity	Dimensionless	Typically 0.85–0.95
ε _g	Globe emissivity	Dimensionless	Typically 0.95
σ	Stefan–Boltzmann constant	W·m ⁻² ·K ⁻⁴	5.67 × 10 ⁻⁸
h	Convective heat transfer coefficient	W·m ⁻² ·K ⁻¹	Depends on wind speed and globe size
SR	Solar radiation	W·m ⁻²	Includes direct and diffuse solar radiation
α _g	Globe albedo	Dimensionless	Approximately 0.05
α _{sfc}	Surface albedo	Dimensionless	Depends on surface material
θ	Solar zenith angle	°	Determines the direction and intensity of incident solar radiation
f _{dir}	Direct-beam fraction	Dimensionless	Ratio of direct solar radiation to total solar radiation

The Liljegren model calculates globe temperature via rigorous physical formulas. Its core algorithm incorporates air temperature (T_a), atmospheric emissivity (ε_a), globe emissivity (ε_g), and globe albedo (α_g) to simulate the effects of terrestrial radiation. To determine precise solar angles, the local latitude and longitude of the construction site, date, and solar time are utilized to derive the solar declination angle and solar hour angle, which subsequently yield the solar zenith angle (θ) required for the computation.

2. Estimation of Field Natural Wet-Bulb Temperature (T_{nwb}):

$$T_{nwb} = T_a - \left(\frac{L}{c_p} \right) \times \left(\frac{e_w - e_a}{P - e_w} \right) \times \left(\frac{1}{1 + \frac{h_r}{h_c}} \right)$$

Table 5 Parameters Used in the Natural Wet-Bulb Temperature Calculation



Symbol	Unit	Parameter	Description / Typical Value
T _{nwb}	°C	Natural wet-bulb temperature	Estimated natural wet-bulb temperature
T _a	°C	Air temperature	Ambient air temperature
L	J·kg ⁻¹	Latent heat of vaporization	Approximately 2,430,000 J·kg ⁻¹ at 25°C
c _p	J·kg ⁻¹ ·K ⁻¹	Specific heat capacity of air	Approximately 1,005 J·kg ⁻¹ ·K ⁻¹
e _w	hPa	Saturation vapor pressure at the wet-bulb surface	Calculated from T _{nwb}
e _a	hPa	Ambient vapor pressure	Calculated from relative humidity and air temperature
P	hPa	Atmospheric pressure	Approximately 1,013.25 hPa at sea level
h _r	W·m ⁻² ·K ⁻¹	Radiative heat transfer coefficient	Determined by radiative exchange
h _c	W·m ⁻² ·K ⁻¹	Convective heat transfer coefficient	Determined by wind speed and wick geometry
σ	W·m ⁻² ·K ⁻⁴	Stefan–Boltzmann constant	5.67 × 10 ⁻⁸

The model accounts for thermal conduction and convection. Its core algorithm integrates the station-side air temperature (T_a), the latent heat of vaporization (L), the specific heat capacity of air (c_p), the saturated vapor pressure at the wet-bulb surface (e_w), and the atmospheric vapor pressure (e_a) to precisely derive the natural wet-bulb temperature corresponding to the field microclimate.

3. Estimation of Field Wet-Bulb Globe Temperature (WBGT): The corrected globe temperature and natural wet-bulb temperature obtained from the Liljegren model, along with the air temperature, are substituted into the outdoor WBGT formula:

WBGT=0.7×T_{nwb}+0.2×T_g+0.1×T_a, thereby yielding high-precision field estimations.

2.5.2 Stage 2: Calibration and Regression

A calibration model mapping the "station-estimated WBGT" to the "field-measured WBGT" is established using paired samples. Grounded in the principles of interpretability and ease of practical on-site application, priority is given to univariable or parsimonious linear regression models. If the residuals exhibit systematic curvature or if errors amplify at the high-temperature extreme, alternative formulations, such as quadratic polynomials, piecewise linear regressions, or interaction models, will be compared.

To evaluate the correlation and accuracy of the calibration models, the coefficient of determination (R^2) is utilized as the data validation tool.

Chapter 3 Results

3.1 Microenvironmental Heat Exposure Analysis Report at the Construction Site

An approximately 2°C difference was observed between field-measured HI and station-derived HI. In terms of heat hazard risk classification, the station-derived HI was mainly distributed in Categories 1 and 2, whereas the field-measured HI was predominantly clustered in Category 3 (Figure 4). This indicates that the difference between station-derived and field-measured HI was sufficient to shift the results into a higher risk category. According to the national heat hazard risk level descriptions in Taiwan, the key distinction between Category 2 and Category 3 is whether personal protective equipment (PPE) is worn. Therefore, relying solely on station-derived HI may lead to underclassification of heat hazard risk, particularly in construction site settings where PPE use is common.

Statistical analysis further confirmed a significant difference between field-measured and station-derived HI values ($p < 0.05$) (Figure 5). Taken together, these findings suggest that station-derived HI may underestimate the actual heat stress level at construction sites. Therefore, field -

based correction or on-site measurement should be considered to improve the accuracy of heat hazard classification and to support appropriate risk management measures.



Further analysis showed that the HI discrepancy was more strongly associated with the temperature difference than with the humidity difference. The correlation between HI discrepancy and temperature difference was $r^2 = 0.895$, whereas the correlation with humidity difference was only $r^2 = 0.136$. Standardized regression coefficients also showed a stronger contribution from temperature than from humidity (0.905 vs. 0.122). These results indicate that the higher field-measured HI was primarily driven by higher on-site air temperature, rather than differences in relative humidity.

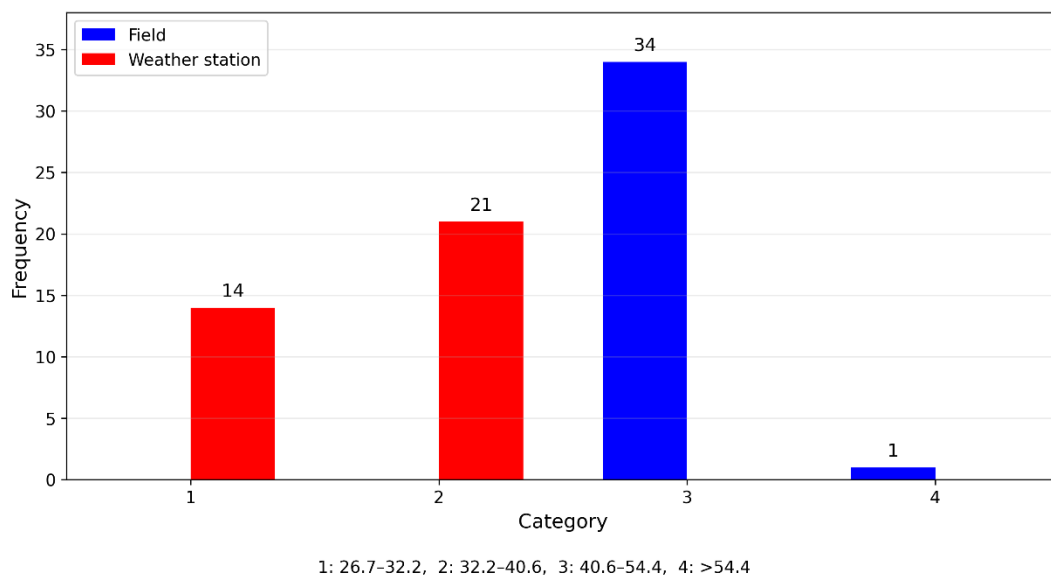


Figure 4 Bar chart of HI risk classifications for the construction site versus the weather station

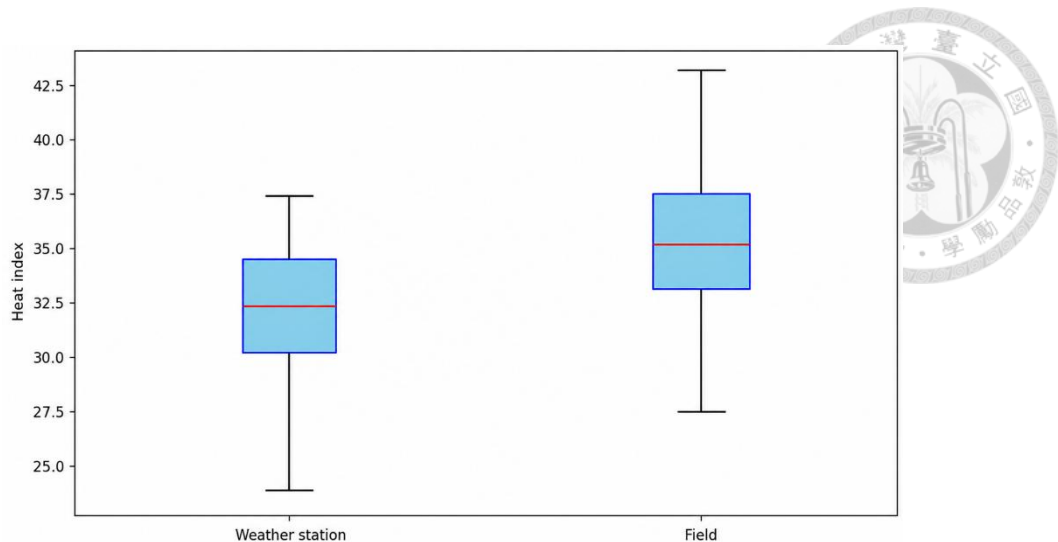


Figure 5 Box plots of HI values for the construction site and the weather station

the field-measured WBGT was mainly distributed in Category 4, whereas the station-derived WBGT was more frequently classified as Category 3 (Figure 6). Although the observed ranges were comparable, with 26.50–31.00°C for field-measured WBGT and 25.50–30.20°C for station-derived WBGT, the approximately 1°C difference between the two measures was sufficient to shift part of the results into a higher risk category. This suggests that station-derived WBGT may still lead to underclassification of heat stress risk when directly applied to construction sites without field-based correction.

Statistical analysis further revealed a significant difference between field-measured and station-derived WBGT values ($p < 0.05$) (Figure 7). Taken together, these findings indicate that relying solely on station-derived WBGT may underestimate the actual heat stress level at construction sites. Therefore, applying field-based correction to station-derived WBGT is necessary to improve the accuracy of heat hazard classification and to support appropriate work-rest management for worker protection

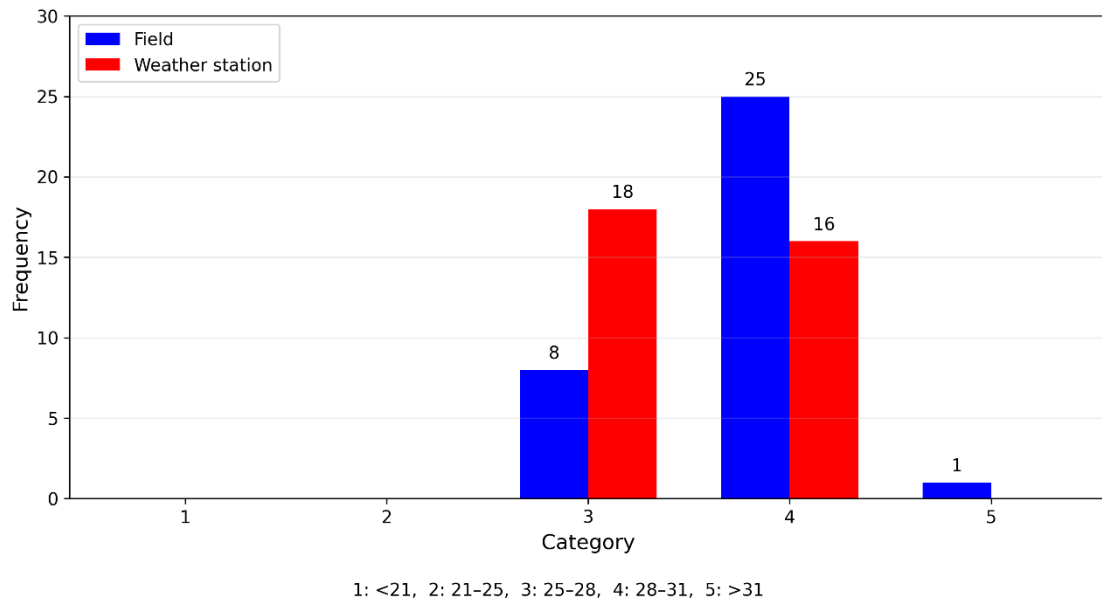


Figure 6 Bar chart of WBGT risk classifications for the construction site versus the weather station

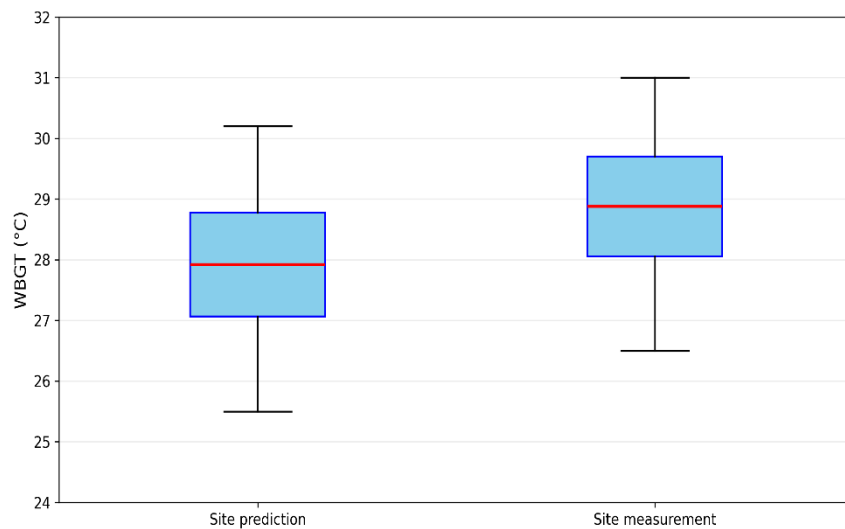


Figure 7 Box plots of WBGT values across different risk classifications for the construction site and the weather station

3.2 Development of an Excel-Based Tool for Calibrating Weather Station Data into Field-Specific WBGT Estimations

The present study has successfully developed an Excel-based tool that calibrates regional Weather Station data into site-specific field WBGT estimations. By bypassing the steep equipment

and labor costs traditionally required for continuous on-site physical monitoring, this technology accomplishes the goal of cost-effective, real-time risk warnings.



Linear regression analysis validated that the values calibrated through this model correlate exceptionally well with actual field measurements, achieving a coefficient of determination (R^2) of 0.9524. (Figure 8) Descriptive statistics further showed that the mean station-derived WBGT was 27.92°C, whereas the mean field-measured WBGT was 28.88°C, indicating that the station-derived WBGT tended to underestimate the field-measured WBGT by approximately 1°C (Table 5). This rigorous regression validation demonstrates that the calibration methodology effectively filters out wide-area macro-meteorological errors, outputting a localized WBGT value that is highly representative of the actual work site environment. Operating on multi-parametric Meteorological Data—including date, localized latitude and longitude, air temperature, relative humidity, wind speed, and atmospheric pressure—this high-performance system integrates real-time observations from the Central Weather Administration. By pairing these parameters with site-specific geographic coordinates and temporal sequences (Figure 9), the tool dynamically derives the natural wet-bulb temperature and globe temperature via the embedded Liljegren model. The calculated air temperature, natural wet-bulb temperature, and globe temperature are then synthesized to output high-accuracy field WBGT estimations (Figure 10). This framework not only bridges the microclimatic gap between macro-meteorological data and localized industrial workplaces, but also drastically curtails corporate expenditures on instrument procurement and sensor maintenance, providing businesses with an early-warning utility that balances operational convenience with scientific precision.

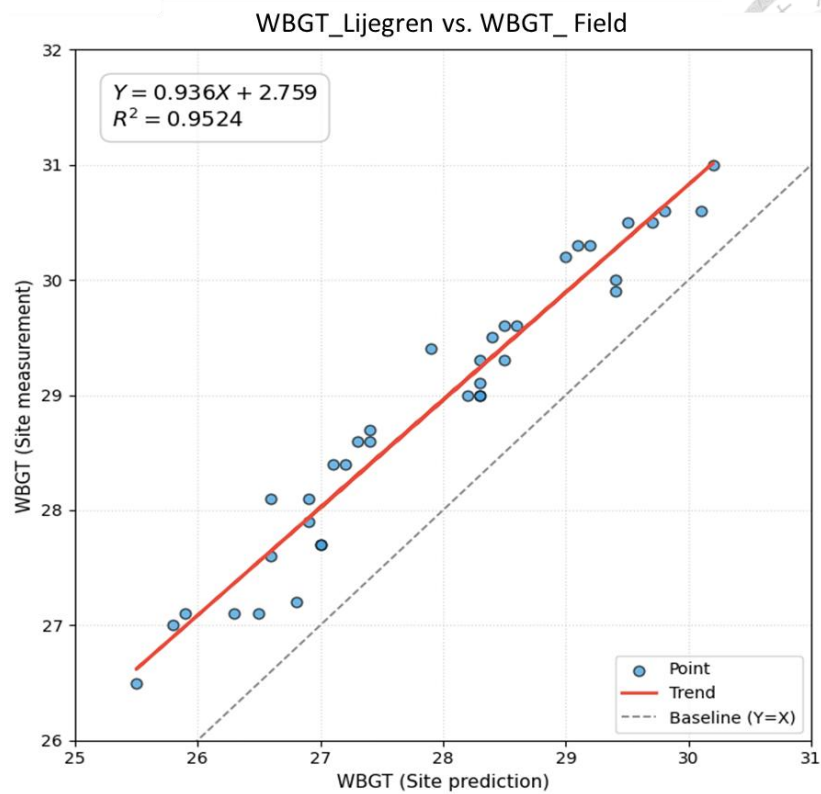


Figure 8 Linear regression between station-derived WBGT and field-measured WBGT.

Table 6 Descriptive statistics of station-derived WBGT and field-measured WBGT

Parameter	WBGT (° C)	
	Mean (SD)	Range
Site prediction (n=35)	27.92 (1.27)	25.50~30.20
Site measurement (n=35)	28.88 (1.22)	26.50~31.00

類別	參數名稱	符號	單位	數值(輸入)	備註/預設值/來源
A. 必要氣象輸入 (至少需要 Ta、濕度、風速、氣壓、短波日射)					
氣象	空氣溫度	Ta	°C	26.0	2 m 乾球溫度 [必填]
氣象	相對濕度	RH	%	75.0	濕度輸入(擇一): RH 或 Td 或 ea [選填]
氣象	露點溫度	Td	°C		濕度輸入(擇一): Td 或 RH 或 ea [選填]
氣象	水氣壓(實際蒸氣壓)	ea	hPa		濕度輸入(擇一): ea 或 Td 或 RH [選填]
氣象	風速 (感測高度)	u	m/s	1.50	建議使用 2 m 風速 (或先換算到 2 m) [必填]
氣象	大氣壓 (站壓/地面壓)	p	hPa	1007.00	若只有 Pa, 請先除以 100 [必填]
輻射	水平面總短波日射(全球輻射)	K↓	W/m²	800	Global Horizontal Irradiance [必填]
輻射	直達日射比例	f_dir	0-1		K↓中屬於直達光的比例 (無資料可留空) [選填]
輻射	太陽天頂角	θz	deg		無資料可留空; 部分實作會用 θz 估算直達分量 [選填]
B. 位置/時間 (用於計算 θz; 若你已直接輸入 θz 可略)					
位置/時間	緯度	lat	deg	23.10111	北緯為正 [選填]
位置/時間	經度	lon	deg	120.28142	東經為正 [選填]
位置/時間	日期	date	YYYY-MM-DD	2026-03-23	Excel 日期格式 [選填]
位置/時間	當地時間	time	hh:mm	08:59	Excel 時間格式 [選填]
位置/時間	時區(相對 UTC)	UTC_offset	hours	8	例: 台灣為 +8 [選填]
C. 地表/長波輻射 (選填; 有 L↓/L↑ 可填, 否則多數實作會以 Ta、RH 等近似)					
地表	地表反射率	α_sfc	0-1	0.20	用於估算地表反射短波 K↑=α_sfc·K↓ [選填]
地表	地表放射率	ε_sfc	0-1	0.95	用於估算地表長波 L↑ [選填]
地表	地表溫度	Ts	°C		若無資料常近似 Ts≈Ta [選填]
長波	下向長波輻射	L↓	W/m²		自動估算: 依 Ta(K)+ea(hPa) 計算 (Brutsaert 晴空近似); 若有觀測/再分析資料可直接覆寫
長波	上向長波輻射	L↑	W/m²		自動估算: L↑=ε_sfc·σ·Ts⁴ (Ts 若空白則用 Ta); 若有資料可直接覆寫
D. 黑球感測器 (Tg) 幾何/光學參數 (標準 15 cm 黑球預設值)					
黑球	黑球直徑	D_g	m	0.150	標準黑球直徑 0.15 m (6 inch) [必填]
黑球	黑球放射率	ε_g	0-1	0.95	Liljegen 常用 ε_g=0.95 [必填]
黑球	黑球反射率	α_g	0-1	0.05	Liljegen 常用 α_g=0.05 (吸收率≈0.95) [必填]
E. 自然濕球感測器 (Tnwb) 濕芯幾何/光學參數 (濕芯圓柱近似)					
濕芯	濕芯直徑	D_wick	m	0.007	Liljegen 常用 0.007 m; ISO 7243 規格約 6±1 mm [必填]
濕芯	濕芯有效長度	L_wick	m	0.0254	Liljegen 常用 0.0254 m; ISO 7243 約 30±5 mm [必填]
濕芯	濕芯反射率	α_wick	0-1	0.40	白色棉紗通常較高反射率; 可調 [選填]
濕芯	濕芯放射率	ε_wick	0-1	0.95	棉紗放射率常接近 0.95; 可調 [選填]
F. 物性常數/計算選項 (通常不用改, 但保留以利一致性)					
常數	史蒂芬-波茲曼常數	σ	W·m⁻²·K⁻⁴	5.67E-08	Stefan-Boltzmann constant [必填]
常數	水蒸氣分子量	M_w	kg/mol	0.01801528	Molecular weight of water vapor [必填]
選項	迭代次數(若你用固定點迭代)	N_iter	count	25	通常 20-30 次已足夠收斂 [選填]

Figure 9 Input interface for weather station parameters, geographic coordinates, local time, and date

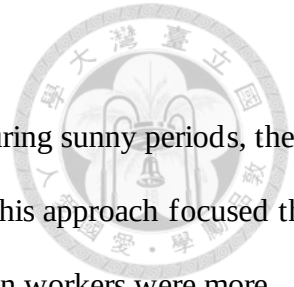
參數	符號	數值	單位	來源/備註
空氣溫度	Ta	26.00	°C	必填
相對濕度	RH	75.0	%	三選一：RH / Td / ea
露點溫度	Td	21.23	°C	三選一：RH / Td / ea
實際水氣壓	ea	25.2111	hPa	三選一：RH / Td / ea
風速	u	1.50	m/s	必填（感測高度同一即可）
大氣壓	p	1007.00	hPa	必填
水平面總短波	K↓	800	W/m ²	必填（全球輻射）
直達日射比例	f_dir	0.835	0–1	選填（未知可留空或用 0.5）
太陽天頂角	θz	50.75	deg	選填（未知可由 lat/lon/time 算）
地表反照率	α_sfc	0.20	0–1	選填
地表放射率	ε_sfc	0.95	0–1	選填
地表溫度	Ts	26.00	°C	選填
下行長波	L↓	0	W/m ²	選填
上行長波	L↑	0	W/m ²	選填
輸出結果（請填入）				
Liljegren 黑球溫度	Tg	26.02	°C	填入推估結果（例如：OSHA WBGT Calculator / 自寫程式）
Liljegren 自然濕球溫度	Tnwb	22.58	°C	填入推估結果（例如：OSHA WBGT Calculator / 自寫程式）
(可選) WBGT(戶外日曬) $= 0.7 * Tnwb + 0.2 * Tg + 0.1 * Ta$		23.61	°C	參考 ISO 7243 戶外日曬公式
校正後 WBGT		24.85	°C	$Y = 0.9356X + 2.7594$
提示：OSHA Outdoor WBGT Calculator 使用 Liljegren (2008) 演算法（輸入為 Ta、RH/Td、風速、氣壓、日射等）。				

Figure 10 Output interface displaying calibrated WBGT values

Chapter 4 Discussion

4.1 General Discussion and Methodological Value

This study evaluated the feasibility of estimating site-specific WBGT in a construction environment using regional weather station data. The results demonstrated that both WBGT and HI differed significantly between the construction site and the weather station ($p < 0.05$), with the field data exhibiting substantially higher variability. This variance highlights the profound impact of construction microclimates—such as variations in solar radiation, structural shading, and localized ventilation—on actual heat exposure. These findings indicate that relying solely on macro-scale meteorological data for occupational heat hazard assessment may lead to substantial underestimation or misclassification of workplace thermal conditions.



Because the most pronounced heat stress at the study site occurred during sunny periods, the analysis was restricted to observations collected under sunny conditions. This approach focused the model development on the periods of greatest occupational relevance, when workers were more likely to experience elevated radiant heat and substantial thermal strain.

Methodologically, this study established a hybrid framework by pairing the Liljegren's model with on-site statistical calibration to map the "weather station-to-field" relationship. Model validation yielded a high coefficient of determination ($R^2 = 0.9524$), demonstrating robust predictive performance. Furthermore, the successfully developed Excel-based tool provides a practical vehicle for real-time application, effectively lowering field-monitoring costs and enhancing operational feasibility.

The core value of this research does not lie in defining a singular, universally applicable formula for all environments, rather, it establishes a standardized modeling workflow based on "physical modeling coupled with localized calibration." This framework enables regional meteorological data to be dynamically adjusted according to distinct site topologies, bringing remote observations closer to the true thermal exposure experienced by workers on the ground.

4.2 Practical Application and Future Scope

The present study has successfully fulfilled its objectives, including the construction of the predictive model, rigorous validation of its accuracy, and the development of a functional deployment tool, thereby serving as a robust decision-support system for thermal risk management. Compared to the exhaustive capital investment required to deploy real-time WBGT instrumentation across an entire enterprise, the method established herein is low-cost, highly accurate, and scalable.

By gathering a limited amount of localized field data from different construction sites or varied configurations in the future, organizations can rapidly train tailored heat-stress warning models, further enhancing the site-specific representation of predictive outcomes.



Consequently, this methodology is not restricted to construction sites; it possesses substantial potential for cross-domain and cross-industry scaling. Potential applications extend to other open-air operations, manufacturing processes involving radiant heat (high-temperature processing), or any dynamic industrial environment requiring proactive, real-time thermal hazard mitigation.

4.3 Limitations

Despite its contributions, several limitations must be acknowledged. First, the predictive model was developed using short-term data from a single construction site, which constrains its generalizability across diverse topographies, construction methods, or extreme anomalies. Second, some weather stations do not provide all required variables, such as global solar radiation. In such cases, data from a nearby station or another validated estimation method may be required, which may introduce additional uncertainty. Finally, the model's extrapolations may exhibit increased uncertainty when future climatic conditions exceed the temperature and humidity boundaries of the current dataset, necessitating conservative safety thresholds under unmodeled extremes.

4.4 Recommendations for Practice and Policy

To maximize the practical and regulatory value of this research, the host organization should continuously aggregate multi-jobsite datasets to construct a standardized microclimatic database and transition toward an automated, real-time early warning system. Such cross-site cumulative data

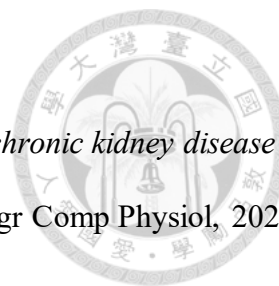
will enable deeper comparative analyses of how distinct microclimatic features affect calibration coefficients, ultimately maturing into a field-ready hazard assessment suite.



From a policy perspective, a gradual transition toward adopting WBGT as the benchmark metric for workplace heat stress is recommended to supplement or replace the current HI. Because WBGT integrates ambient temperature, humidity, wind velocity, and radiant heat, it aligns far more accurately with the physiological strain borne by outdoor laborers. Furthermore, government authorities and enterprises should establish formal calibration mechanisms to translate macro-forecasts into site-specific conditions, eliminating microclimatic disparities that cause risk underestimation. Clinically and administratively, these calibrated WBGT outputs should be structurally integrated with actionable field controls, including mandatory work-rest cycles, systematic hydration, engineered shading, and PPE adjustments, thereby effectively reducing the incidence of heat-related illnesses.

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