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Development of a Safety Management Support System for Construction Sites Using Pinpoint Weather Forecast Information

Moe SHIGAKI[1]*, Kentaro HAYAKAWA[2], Hiroyuki AKITA[3], Michiko SHIMIZU[4], Mika SAKURAMOTO[5]

[1] *Hazama Ando Corporation, Japan,* E-mail address: shigaki.moe@ad-hzm.co.jp
[2] *Hazama Ando Corporation, Japan,* E-mail address: hayakawa.kentaro@ad-hzm.co.jp
[3] *Hazama Ando Corporation, Japan,* E-mail address: akita.hiroyuki@ad-hzm.co.jp
[4] *Hazama Ando Corporation, Japan,* E-mail address: shimizu.michiko@ad-hzm.co.jp
[5] *Life & Business Weather Inc., Japan,* E-mail address: sakuramoto-m@lbw.jp

Abstract: The increasing occurrence of abnormal weather conditions such as unusually heavy rains and strong winds adversely affects construction work. However, although these phenomena are localized, conventional weather forecasts have insufficient spatial resolution and update frequency to accurately predict weather conditions at construction sites. To address this issue, we introduced a pinpoint weather forecasting technology that improves spatial resolution and update frequency. The weather information obtained from this technology is processed and provided to construction sites in a comprehensible state, which enables construction workers to better prepare for weather conditions, thereby reducing the risk of accidents and delays. Furthermore, a safety management system was developed based on the relationship between weather and labor accidents. Predicting workplace accidents that are likely to occur on that day based on the impact of weather on the body enabled performing safety awareness activities, such as morning and lunch meetings, from a new perspective, improving safety awareness among construction workers and reducing the number of accidents on construction sites. This paper describes the development process of the proposed system and the utilization of weather forecasting at construction sites, which can be applied to other industries and contribute to improving safety and efficiency in various fields.

Key words: pinpoint weather forecast, construction sites, labor accidents, safety awareness activities, biometeorology, data science

1. INTRODUCTION

In recent years, abnormal weather events such as guerrilla heavy rains have frequently occurred owing to global warming. Guerrilla heavy rains may disrupt the balance between precipitation and drainage, leading to major disasters. In 2008, an accident occurred in Tokyo where the water level in a pit suddenly rose during sewer construction, causing the death of a worker. In 2013, a large amount of rainwater in Nagoya flowed into a shield construction site, causing flooding. Thus, countermeasures against heavy rains have become a standard for safety management.

Weather conditions sometimes affect construction, such as strong winds at high altitudes or low temperatures at unexpected times, leading to delays or deterioration in the quality of structures. For example, the wind speed may increase at high altitudes, and nets installed to prevent sand from scattering may move owing to wind, causing the suspension of the work. In concrete pouring management, the points to be noted for pouring under low or high temperatures are clearly defined to prevent quality deterioration. However, extremely low temperatures may occur in the early morning owing to radiative cooling even in late autumn; thus, measures against early frost damage are required.

Thus, weather information is closely related to quality and safety management in construction work. By correctly understanding the relationship between the two, it may be possible to appropriately respond to unforeseen situations caused by weather during construction. Table 1 summarizes the relationship between construction work and weather information.

Table 1. Relationship between construction work and weather information

Meteorological information	Relationship between construction work and weather information
Rainfall, Snow	The sooner and more accurately we know when and how much rain (or snow) will fall, the sooner we can take action in advance.
Lightning	Understanding the possibility of lightning strikes is crucial when managing explosives or conducting electrical installations. Moreover, lightning often occurs simultaneously with heavy rain and gusty winds.
Temperature	Temperature control is essential when placing and curing concrete in hot and cold weather. Additionally, temperature information is useful for heatstroke prevention.
Gust	Obtaining wind speed information at different altitudes can greatly contribute to preventing crane tipping, material scattering, and odor dispersion.
Wave	For marine and coastal construction, it is crucial that wave forecast values are displayed in the construction standards.

The fundamental technology used to solve these issues is pinpoint weather forecasting [1], which predicts the weather at any location with high temporal and spatial resolution. The authors have deployed pinpoint weather forecasts to construction sites and collected their data. Based on the results, they demonstrated more effective ways to utilize pinpoint weather forecasts and discussed new ways to use weather forecasts at construction sites, leading to the development of new technologies [2]. Examples of these efforts include

(1) reusing previously announced weather forecast values as evidence of work implementation;

(2) utilizing upstream river rainfall forecast values for downstream work planning and evacuation forecasts;

(3) linking pinpoint rainfall forecast data with sedimentation tank water level sensors to operate drainage gates without waste;

(4) combining dust scattering amounts for each construction machine with weather information to predict the amount and direction of dust scattering hourly;

(5) analyzing the relationship between labor accident data and weather information to predict the possibility of labor accidents in advance using heat stroke prediction as a hint.

In this paper, we introduce the essential function (1) of the system to apply the above five items to construction sites in Chapter 2. Furthermore, we introduce the development of technology (5) as an advanced utilization of weather data in Chapter 3 and describe its applications.

2. USE OF PINPOINT WEATHER FORECASTING FOR CONSTRUCTION SITE MANAGEMENT

2.1. Overview of pinpoint weather forecasting

Pinpoint weather forecasting adopts the development technology Kiyomasa Pro by Life Business Weather Co., Ltd. (LBW). This technology builds a dedicated weather information site on the internet for any point and provides forecasts. It can always view the latest weather forecasts and issue warnings when forecasts exceed specified work stoppage criteria based on rainfall and wind speed.

The deployment of pinpoint weather forecasting to construction sites facilitates the following construction management activities:

(1) Accurate judgment of whether to stop or continue construction

Because forecasts are provided in a detailed forecast range of 1 km^2 based on the latitude and longitude of the site, it is possible to grasp weather changes at the site, providing a reliable basis for judgment. In addition, because the amount of precipitation is forecast in units of 0.1 mm, the intensity of rainfall can be accurately determined.

(2) Planning of the work schedule

Local weather information (weather, rainfall, wind direction and speed, temperature, and humidity) is provided every hour up to 36 h in advance, making it possible to plan work at the morning meeting until the next evening. Moreover, since the information is updated every 30 min, observed values from rain cloud radar, etc., are constantly reflected, and the latest information can be used for judgment.

(3) Predicting the need for changes in the day's work [3]

Especially for precipitation, forecasts are provided every 5 min up to 60 min in advance, making it possible to predict the occurrence of sudden heavy rain. In addition, lightning and tornado predictions are provided in the same way, serving as a basis for deciding whether to stop work immediately.

(4) Accurate risk management for high-altitude work

Since the wind direction and speed are calculated up to a height of 600 m in units of 10 m, it is possible to accurately judge whether to stop or continue high-altitude work.

(5) Prediction of reaching the work stoppage criteria

By entering the site-specific work stoppage criteria (e.g., precipitation of 20 mm/h or more, strong wind of 10 m/s or more, and so on) into the system, an alert can be activated via e-mail, etc., when the corresponding forecast is announced.

The screen configuration of the pinpoint weather forecast is shown in Figure 1.

①	**Project**
②	**Weather radar images**
③	**Regulation of to stop the work**
④	**Local area forecast (weather, precipitation, wind direction and wind speed, temperature, humidity)**
⑤	**Wind direction and wind speed**

Figure 1. Example of a pinpoint weather forecast system screen

2.2. Addition of the evidence creation function

The information on whether the proposed technology has been implemented as proposed is compiled as a document and inspected in the comprehensive evaluation bidding system used in public works [4]. In daily life, weather forecasts involve information for the day, and there is little need for past forecast values. We hypothesized that forecast values themselves can be valuable in construction work and developed a function to record past forecast values as evidence of business implementation. In other words, by recording the basis for deciding to stop work in abnormal or unexpected weather conditions as a numerical value, we considered the following use cases:

(1) creation of documents that show the basis for decisions, such as stopping or extending the construction period;

(2) data storage at the time of concrete placement or during abnormal weather;

(3) submission of documents to the ordering party as proof of performance in technical proposals.

In addition, this system can retrieve data retrospectively and obtain observation data from AMeDAS near the site, forecast data from pinpoint weather forecasts, and the history of alert mail transmissions from the website.

3. WEATHER-RELATED LABOR ACCIDENT PREDICTION TECHNOLOGY

3.1. Development of weather-related labor accident prediction technology

Safety management is an indispensable element in managing construction sites. We perform safety awareness activities daily, proceed with work according to work procedures and plans, and conduct safety patrols [5]. However, the number of deaths due to labor accidents is still the highest in the construction industry, accounting for 36% of all industries [6]. In particular, many labor accidents occur owing to heatstroke from May to September [7]. As mentioned in Chapter 2, a pinpoint weather forecast system can raise awareness about heatstroke based on information on temperature and humidity. On the other hand, no system has been developed to associate weather elements with the occurrence of other labor accidents and predict them. We speculated that weather elements and labor accidents due to reasons other than heatstroke can also be correlated and found a correlation between the two by analyzing past labor accident and weather data. By combining this correlation with pinpoint weather forecasting, we developed a weather-related labor accident prediction technology to predict labor accidents, which is described in this chapter.

3.2. Labor accident data and weather data used for analysis

The labor accident data used for the analysis involved 743 cases that occurred at Hazama Ando Corporation's construction sites from April 2013 to March 2016, resulting in an absence of either more than 4 days or less than 4 days. These cases were divided into 11 types, excluding heatstroke (160 cases), those that involved traffic accidents, and personal illness (Figure 2).

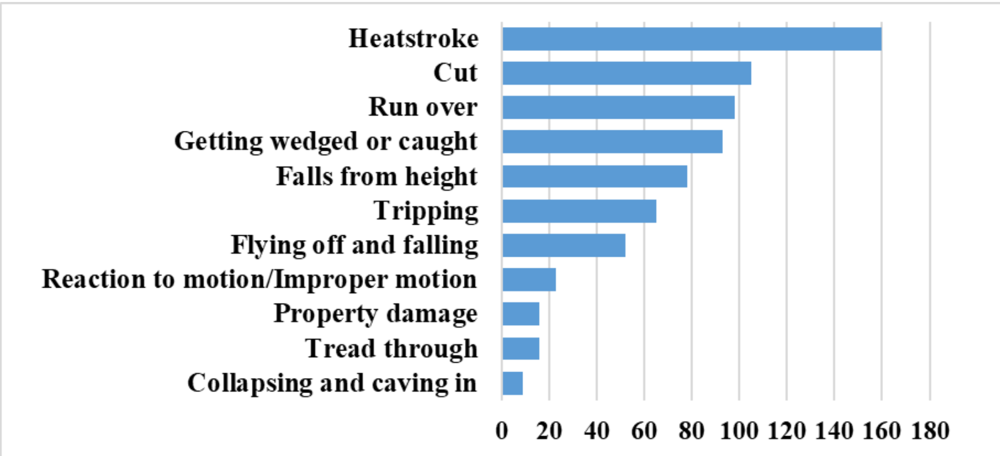


Figure 2. Number of labor accidents by type

A total of 266 items of meteorological data were set based on a combination of meteorological elements and statistical values for a certain period at the location where the labor accident occurred. In particular, the daily temperature, humidity, atmospheric pressure, sensory temperature, and discomfort index were extracted for each of the seven days preceding the date of the labor accident, and combinations of data such as the highest value, lowest value, average value, standard deviation, daily range difference (difference between the highest and lowest values in a day), difference from the previous day, and amount of change (slope) were used for each of these weather elements (Figure 3).

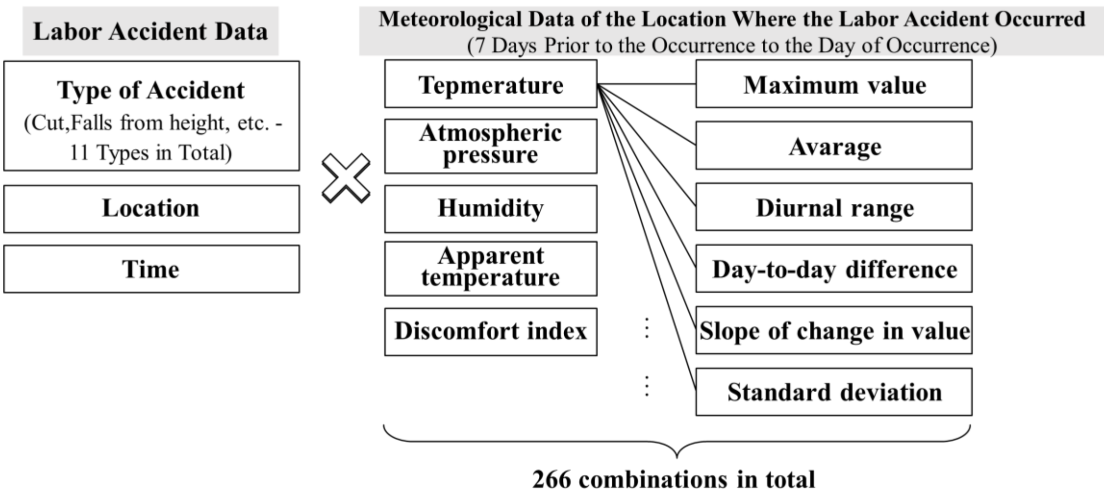


Figure 3. Combination of labor accident data and weather data

3.3. Data analysis method

Further, we explain the analysis method and results that were obtained to clarify the relationship between labor accident data and weather data. To confirm whether specific weather data affect the occurrence of labor accidents, we conducted an analysis of variance on 11 types of labor accidents and 266 types of weather data, as shown in Figure 4. We interpreted the results by setting a "significance level" for the calculated p-value. If the p-value was less than 1% significance level, it was interpreted as "highly significant," and if it was between 1% and 5% significance levels, it was interpreted as "significant" and used to identify the "factors that have an impact" [8]. Significance indicates that the set weather element is involved in the occurrence of that type of labor accident.

Figure 4 shows a box plot of whether there was a significant difference in the maximum humidity on the day when heatstroke and other labor accidents occurred. The interquartile range of the box plot representing heatstroke occurrence shows a higher maximum humidity than that of the box plot representing other labor accidents. When expressed as p-values, the significance level is 5×10^{-7}%, indicating that it is highly significant and that the occurrence of heatstroke is related to the maximum humidity on the day.

Figure 5 shows a box plot of the significant difference in the maximum pressure difference between 4 and 3 days prior to heatstroke and other labor accidents. The interquartile range of both box plots is located at the same position, and the p-value is 60%, indicating no significant difference. In other words, the maximum pressure difference 4 or 3 days prior to the accidents is not related to the occurrence of heatstroke.

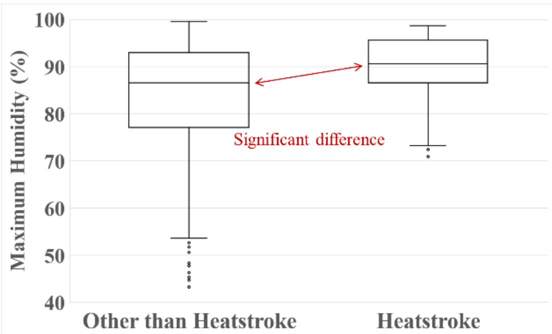


Figure 4. Box plot (significant difference)

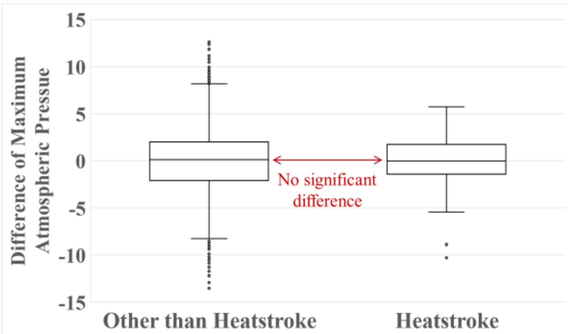


Figure 5: Box plot (no significant difference)

3.4. Analysis results

The results of the analysis of variance are shown in Table 2, where less than 1% significance level is represented by ○, and 1%–5% significance level is represented by △. A significant relationship with some weather elements was observed in all 11 types of labor accidents. Among the five weather elements, labor accident types with a significant relationship with all weather elements were classified as "correlated with weather," and those correlated with four or fewer weather elements with a significant relationship were classified as "somewhat correlated with weather." Moreover, property damage and collapse/fall accidents with few occurrences were classified as "somewhat correlated with weather."

Table 2 shows that getting caught and falling/dropping are "highly significant" for all weather elements, indicating that these accidents can be reduced by paying attention to daily weather data. In falling/dropping accidents, 61 weather elements out of 266 items showed a significant relationship with other labor accidents (Table 3 shows the top 5 weather elements related to falling/dropping accidents). The top item shows the difference in minimum perceived temperature between two days and one day before the occurrence of the labor accident. We found that falling/dropping accidents tend to occur when the difference is large. The second item shows the case when the temperature difference with that 48 h before the occurrence of the labor accident was large. Looking at the others, weather elements related to this accident are largely related to temperature and humidity up to two days before the occurrence of the accident. By comparing the results of the analysis of variance for other labor accidents, the weather conditions at the time of falling/dropping accidents were characterized by "low humidity on the day of the accident," "large daily change in atmospheric pressure," and "large change in perceived temperature up to two days before the occurrence." These results showed that the weather conditions related to temperature, humidity, and wind rapidly changed in the two days that led up to the occurrence of falling/dropping accidents.

From a biometeorological perspective [9], a greater temperature difference increases the fluctuation in blood pressure and the impact of stress on the body [10]. This can be confirmed using Table 3, where weather elements related to perceived temperature difference accounted for two out of the top 5 items, and when focusing on the 48 h before the occurrence of falling/dropping accidents, 94% of cases had a perceived temperature difference of 5 degrees or more (when all cases of falling/dropping accidents were used as the denominator). Therefore, the rapid temperature changes in the two days that led up to the occurrence of the accidents made it difficult for the body to keep up, increasing the likelihood of human error and resulting in falling/dropping accidents.

Table 2. List of weather elements correlated with labor accidents

Accidents＼meteorological element	**Temperature**	**Atmospheric pressure**	**Humidity**	**Apparent temperature**	**Discomfort index**	**Correlation between weather information and types of accidents**
Cut	○	○	△	○	△	Correlation
Flying off and falling				△	△	Slight correlation
Getting wedged or caught	○	○	○	○	○	Correlation
Tripping	△	○	△	△	△	Correlation
Falls from height	○	○	○	○	○	Correlation
Run over and clash	○	○	△	○	○	Correlation
Reaction to motion/ Improper motion	○	△		△	○	Slight correlation
Collapsing and caving in	○	○	○	○	○	Slight correlation
Tread through			△			Slight correlation
Property damage	○	○	△	○	○	Slight correlation

○：The significance level is less than 1%　△：The significance level is 1% or more, and less than 5%

Table 3. Top 5 weather elements related to falling/dropping accidents

Ranking	**Meteological elements that showed a significant diggerence against other types of accidents**			**p-values**
	Period from the day of accident occurrence	**Meteorological element**	**Scale**	
1st	Between two days and one day before	Minimum apparent temperature	Large difference	0.01%
2nd	48 hours before	Maximum and minimum temperature	Large difference	0.03%
3rd	On the day	Minimum humidity	Small value	0.06%
4th	One day before	Maximum and minimum apparent temperature	Large difference	0.06%
5th	On the day	Average humidity	Small value	0.06%

3.5. Information obtained from this technology

To apply this technology to actual construction sites, we conducted a trial with 45 workers at 23 construction sites of Hazama Ando Corporation, collected their opinions on how to use the system and what information they felt was necessary, and built the system called weather hazard prediction technology based on their opinions. Figure 7 shows the screen of the completed system. Since the relationship between labor accidents and weather elements was clarified using the analysis results, labor accidents can be predicted based on the results of pinpoint weather forecasts. By comparing the weather information from the previous day and the past few days with the analysis results, we identified labor accident types that occurred in the past and used them as safety information.

The screen shown in Figure 6 can be viewed on digital signage or a PC installed at the construction site. The information displayed includes “likely accidents,” “past cases,” and “pinpoint weather forecasts,” with past cases being labor accident cases that occurred in the past, thereby raising awareness by providing specific examples. On the next screen, the body's attention level due to weather is displayed, as shown in Figure 7. This screen considers the impact of weather on the body from a biometeorological perspective and explains why certain types of labor accidents are more likely to occur. In particular, it explains the effects of weather elements on blood vessels, blood pressure, heart rate, muscles, and bronchi. For example, when the temperature drops and the body feels cold, blood vessels contract, blood pressure rises, and heart rate increases. In addition, muscles tense up and the body becomes stiff, making careless mistakes more likely to occur, such as dropping objects. This information is important for pinpointing weather forecasting and improving safety awareness activities at construction sites to prevent labor accidents. Furthermore, weather-related labor accident prediction technology can be developed based on this knowledge.

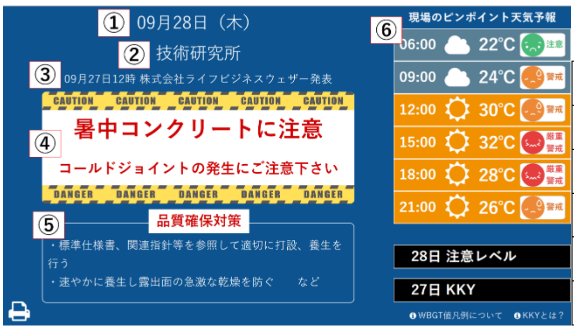
①	Forecast date
②	Project
③	Announcement date
④	Labor accidents that are likely to occur on that day
⑤	Labor accident cases thet have occurred in the past
⑥	Local area forecast

Figure 6. System top page

①	Forecast date
②	Impact on the body (Vasoconstriction/Vasodilation, Blood pressure increase/decrease, Heart rate increase/decrease, Muscle tension/relaxation, Bronchial dilation/constriction)
③	Explanation of likely occupational accidents considering the above impacts

Figure 7. Impact of weather on the body from a biometeorological perspective

Furthermore, when special points must be noted during construction owing to unique weather conditions, such as extremely high or low temperatures, a screen displaying warnings and measures for quality assurance is displayed, as shown in Figure 8. In addition, information can be provided via e-mail on a smartphone, allowing users to choose a format that is easy to use on the construction site.



①	Forecast date
②	Project
③	Announcement date
④	Precautions during construction due to special weather conditions
⑤	Warnings and measures for quality assurance
⑥	Local area forecast

Figure 8. Warnings and measures for quality assurance

3.6. Utilization and application of the technology at construction sites

The information obtained from this technology is delivered as a forecast the next day at 11:00 a.m. every day. This information can be used to determine safety instructions for the next day and can be disseminated during lunchtime meetings. By displaying this information on digital signage during the morning meeting the next day, the entire construction site can be made aware of it, and during safety awareness activities, actionable goals can be set with awareness of the likelihood of labor accidents. Conventional safety awareness activities that were repeated daily in the past were based on imagination and experience. Using the predicted alerts based on weather data analysis in safety awareness activities, potential events can be predicted from a new perspective beyond the intuition and knowledge of individuals.

Currently, this technology has already been employed in multiple construction sites and evaluated as "when accidents that are likely to occur are introduced during morning and lunch meetings, interested staff and workers are obtaining information from digital signage themselves, and it is leaving an impression," implying that the introduction of this technology improves the safety awareness of construction site workers.

4. CONCLUSION

Weather considerably impacts construction sites, and weather information is crucial for ensuring quality and safety management. Construction losses and weather disasters can occur owing to adverse weather conditions. Therefore, attention must be paid to weather information around the construction site. Pinpoint weather forecasts have been developed that can perform weather forecasts with high spatial and temporal resolution. This technology can enable detailed site management by predicting sudden weather changes in advance. In addition, we developed a new system called weather hazard prediction, which combines weather information and labor accident data to expand the scope beyond safety management to health management. Using weather information, we have contributed to raising the awareness of quality and safety management at construction sites.

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