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Analysis on Rock Probability of Embedment Pile into Rock Mass for Pile Group at Building Sites in Karst Terrain

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Abstract

The complex karst foundation has discontinuous fluctuations on rock surfaces and uncertainties in cave-fissure development, making it impossible to determine the depth of embedment pile into rock mass and impossible to reasonably predict difficulty in pile construction, which results in lack of reliable support for the feasible evaluation of the pile foundation and selection of its construction methods. Based on the study of the rock embedding probability model for single pile at building sites in karst area, according to the site engineering survey data, this paper further proposes a method to determine the average rock embedding elevation of pile groups and at last verifies the rationality of the proposed model with a project instance. The results show that there might be a great deviation if the construction survey hole entering the rocks is considered as the piles entering the rocks; the proposed rock embedding probability model for piles considers the effects of pile diameter and foundation dissolution characteristics on embedment pile group into rock mass and thus can correctly reflect the elevation distribution of the rock embedding probability of pile groups; the average rock embedding elevation of pile groups determined by the proposed rock embedding probability model for pile groups in the detailed survey stage can meet the accuracy requirement in the feasibility study of the pile foundation in the design stage. The average rock embedding elevation of pile groups determined in the construction survey stage can provide basis for the selection of pile construction methods and give the last chance to verify the rationality of pile foundation.

Keywords

Karst, Pile groups, Pile embedding into rock.

1. Introduction

There may be significant differences in the rock surface undulation and cave-fissure development characteristics of different karst sites, so there is a great uncertainty in the rock embedding depth of rock-embedded piles, which is the main reason for the various pile construction difficulties at different karst sites. Therefore, reasonable prediction of the rock embedding depth of the karst piles in the survey stage can provide basic support for the feasibility study of the pile foundation and the selection of pile construction technologies.

The detailed survey on karst foundation is carried out mainly to find out the karst development law and focuses on the qualitative analysis on the influencing factors to karst process and the scale and density of morphological characteristics of karst [1-4] or classification of karst foundation based on this [5-9], so as to provide main support for the feasibility study of the pile foundation in the foundation design stage. However, this method and idea can neither reasonably predict the rock embedding depth range of the pile group nor give realistic evaluation of the pile construction difficulty. Before the construction of piles, construction survey with one survey hole with the scope of pile, usually would be carried out, and the rock embedding depth of the survey hole at the pile position would be considered as that of the pile hole. However, the diameter of the survey hole is quite smaller than that of the pile hole, so the rock embedding depths of the two often have significant errors. As a result, in actual engineering practice, it is often inevitable to carry out one or more supplementary surveys, and even repeated foundation design alteration or construction process changes, so the technical economics of the pile foundation is quite different from the evaluation results in the design stage. In the karst survey, engineering geophysical technologies like high-density electrical method [10] and geological radar [11] can help obtain continuous geological profiles and reveal the rock surface undulation characteristics and cave-fissure distribution range, which takes less detection cost and shorter time, but engineering geophysical technologies are affected by various environmental conditions

[12, 13], so its detection accuracy and depth are difficult to meet the engineering accuracy requirements for pile foundations. In summary, the rock embedding of pile groups at karst sites is still difficult to reasonably predict at the survey stage, and the related issues still need further studies.

According to the depth distribution law of the dissolution at building site in karst terrain [14], a rock embedding probability model for singe pile has been established based on pile construction survey [15]. Based on this, this paper further establishes rock embedding probability model for pile group with the same diameter at building sites, and demonstrates its engineering accuracy through a project instance. The research results can be used to predict the average rock embedding elevation of embedded piles and to provide reasonable basis for the technical economic feasibility study of the pile foundation for building foundation in karst terrain.

2. Calculation Method for Rock Embedding Probability of Pile Groups

Suppose the rock embedding condition for survey holes is the same as that for piles, which requires that there should be no karst cave developed within a certain depth range, then the lower limit H_a and the upper limit H_b used to calculate the elevation can be determined using Formula (1):

$$\left.\begin{aligned} H_a &= \Delta H \cdot \mathrm{int}\left(\frac{H_{\min}}{\Delta H}\right) \\ H_b &= \Delta H \cdot \left[\mathrm{int}\left(\frac{H_{\max}}{\Delta H}\right) + 1\right] \end{aligned}\right\} \tag{1}$$

where: H_{min} is the minimum rock embedding elevation of the survey hole; H_{max} is the maximum rock embedding elevation of the survey hole; int() is the rounding function.

Let the interval length be ΔH and the bottom elevation of each interval be $H_i \in [H_a, H_b)$. As elevation decreases, the sequence is: $H_1 > H_2 > \ldots > H_{i-1} > H_i > H_{i+1} > \ldots$

If the survey hole above the elevation H is embedded into rocks, but the corresponding pile hole is not, then the rock embedding probability of the pile hole at elevation H is [14]:

$$\eta^D = (1 - r)^{\frac{4}{3}(10D-1)r} \tag{2}$$

where: η^D is the rock embedding probability of the pile hole with a diameter of D; D is the diameter of the pile hole; r is the dissolution ratio at elevation H and a function of elevation H, The specific expression is as follows:

$$r = ae^{b(H-H_0)} \tag{3}$$

where: a and b are constants, and H_0 is the initial elevation.

In a smaller elevation range $(H_{i-1}, H_i]$, the rock embedding probability of the foundation pile at the center of the interval can be used to represent the average rock embedding probability of the foundation pile. The specific calculation formulas are as follows:

$$\begin{cases} \eta_i^D = (1 - r_i)^{\frac{4}{3}(10D-1)r_i} \\ r_i = ae^{b(H_i + \Delta H - H_0)} \end{cases} \tag{4}$$

where: η_i^D is the average rock embedding probability of the foundation piles within the interval $(H_{i-1}, H_i]$; r_i is the dissolution ratio at the center of the interval $(H_{i-1}, H_i]$; for the meanings of the other symbols, please refer to the preceding paragraphs.

Pile holes embedded into rocks within the elevation interval $(H_{i-1}, H_i]$ can be classified into two types: one is that the rock embedding elevations of survey holes are above the interval $(H_{i-1}, H_i]$ but that those of the pile holes are within the interval $(H_{i-1}, H_i]$, such as Pile A in Figure 1; the other type is that the rock embedding elevations of both survey holes and pile holes are within the interval $(H_{i-1}, H_i]$, such as Pile B in Figure 1.

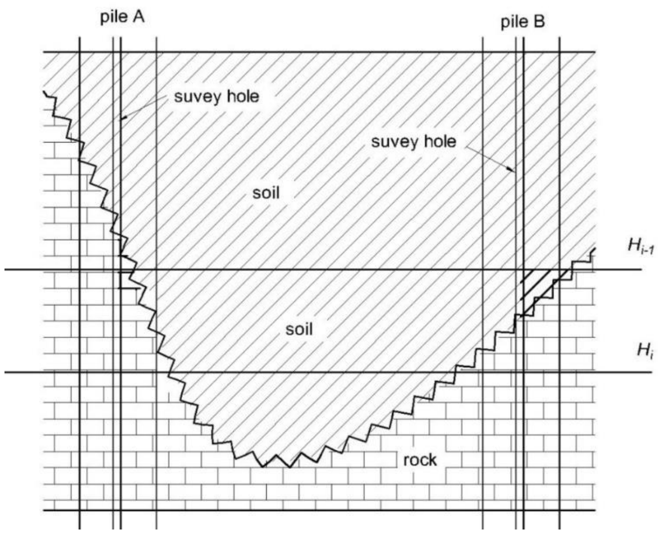

Fig.1. rock-embedding relations between survey hole and pile

Formula (4) is mainly applicable to piles that may be embedded into rocks, so when calculating the rock embedding probability within the range (H_{i-1}, H_i], one should calculate the probabilities of piles definitely and possibly being embedded into rocks, respectively.

The number of Type I embedded piles in the elevation interval (H_{i-1}, H_i] is determined based on the number of piles not embedded above this interval $\overline{N}_{i-1}^{D}$, which is calculated according to the following formula:

$$\overline{N}_{i-1}^{D} = N_{i-1}^{d} - N_{i-1}^{D} \tag{5}$$

where: N_{i-1}^{D} is the accumulative number of embedded survey holes above the elevation H_{i-1}; N_{i-1}^{D} is the accumulative number of embedded piles above the elevation H_{i-1};

After obtaining $\overline{N}_{i-1}^{D}$, calculate the number of Type I embedded piles in the elevation interval (H_{i-1}, H_i] according to the following formula:

$$A_i^D = \eta_i^D \overline{N}_{i-1}^{D} \tag{6}$$

Substitute Formula (5) into Formula (6), and the following formula can be obtained:

$$A_i^D = \eta_i^D \left(N_{i-1}^{d} - N_{i-1}^{D}\right) \tag{7}$$

Let the number of the embedded survey holes in the elevation interval (H_{i-1}, H_i] be n_i^d, and then the number B_i^D of Type II embedded piles in the interval (H_{i-1}, H_i] is:

$$B_i^D = \eta_i^D \cdot n_i^d \tag{8}$$

The sum of the number of embedded piles of the above two types in the elevation interval (H_{i-1}, H_i] is:

$$n_i^D = A_i^D + B_i^D \tag{9}$$

Substitute Formula (7) and (8) into the above formula, and the following formula can be obtained:

$$n_i^D = \eta_i^D \left(n_i^d + N_{i-1}^d - N_{i-1}^D \right) \tag{10}$$

Because

$$N_i^d = n_{i-1}^d + N_{i-1}^d \tag{11}$$

where: N_i^d is the accumulative number of survey holes above the elevation H_i.

Substitute Formula (11) into Formula (10), and the following formula can be obtained:

$$n_i^D = \eta_i^D \left(N_i^d - N_{i-1}^D \right) \tag{12}$$

Let the total number of piles at the site be n, and the rock embedding probability p_i^d of the survey holes in the elevation interval (H_{i-1}, H_i] and the rock embedding probability p_i^D of piles are defined as follows:

$$\begin{cases} p_i^d = \dfrac{n_i^d}{n} \times 100\% \\ p_i^D = \dfrac{n_\mathrm{i}^D}{n} \times 100\% \end{cases} \tag{13}$$

The rock embedding probability P_i^d of survey holes above the elevation H_i and the rock embedding probability P_i^D of pile groups are as follows:

$$\begin{cases} P_i^d = \dfrac{N_i^d}{n} \times 100\% \\ P_i^D = \dfrac{N_\mathrm{i}^D}{n} \times 100\% \end{cases} \tag{14}$$

Substitute Formula (13) and (14) into the Formula (12), and the following formula can be obtained:

$$p_i^D = \eta_i^D \left(P_i^d - P_{i-1}^D \right) \tag{15}$$

where: P_{i-1}^D is the accumulative rock embedding probability of piles above the elevation H_{i-1}.

In engineering practice, more attention is paid to the total rock embedding probability P_i^D of the pile holes above the elevation H_i. p_i^D can be written as:

$$p_i^D = P_i^D - P_{i-1}^D \tag{16}$$

Substitute Formula (15) into Formula (16), and the following formula can be obtained:

$$P_i^D = \eta_i^D \left(P_i^d - P_{i-1}^D\right) + P_{i-1}^D \tag{17}$$

From Formula (17), it can be seen that, the rock embedding probability curve of foundation piles and the rock embedding curve of survey holes are the main basis for determination of the rock embedding probability curve of pile groups. These are determined according to the survey data and no extra test work is needed. The data sources are cheap and abundant and the method is highly specific and operable, and thus it can be easily promoted and applied in engineering practice.

4. Project Instance

4.1 Project Profile

Jinhao Garden of Pingguo County is located in Xingping Road, Pingguo County. The building is L-shaped, with a length of 70.4m and a width of 30.6m. There are 12~13 floors above the ground and 1 floor underground. The formation of the site is made up of plain fill, red clay and limestone, with the complete limestone as the pile tip bearing stratum.

By building shape and size, the site is divided into three subareas, namely east area, mid area and west area. There are 34 piles in the east area, 43 in the west area and 40 in the west area, with a diameter of 1.0m. Pile construction survey holes should be arranged one a one-pile-one-hole basis. According to the drilling results, the cave-fissure development is summarized in Table 1. The floor plan for the pile foundations is shown in Figure 2. According to the method provided by the reference [14], the dissolution ratio curve of each area is shown in Figure 3.

It can be seen from Table 1 that the cave-encountering rate of the site is 55.56~88.37% and that the line karst rate is 11.69~22.84%. The karst at the site is strongly developed, and thus it is a typical karst site and highly representative of the engineering conditions.

Tab.1. Site survey profile

Area	Survey stage	N	N_{cave}	L_{cave} /m	L/m	α/%	β/%	dissolution ratio fitting formula $r=ae^{b(H-101)}$		
								Coefficient a	Coefficient b	Correlation coefficient R
East	Detailed survey	9	5	10.30	88.08	55.56	11.69	61.421	-0.2216	0.815
	Construction survey	34	24	76.65	436.24	70.59	17.57	70.251	-0.2230	0.959
Mid	Detailed survey	7	6	14.74	72.96	87.50	20.20	73.649	-0.2242	0.894
	Construction survey	43	38	94.27	478.09	88.37	19.72	84.659	-0.2241	0.966
West	Detailed survey	8	6	19.30	84.50	75.00	22.84	73.977	-0.1494	0.840
	Construction survey	40	29	112.46	512.09	70.73	21.96	80.175	-0.1744	0.941

Note: The header in the table above, symbol 'N' refers to sum of survey holes; symbol 'N_{cave}' refers to sum of Survey holes with caves; symbol 'L_{cave}' refers to total thickness of caves; symbol 'L' refers to total thickness of rocks disclosed by survey hole; symbol 'α' refers to ratio of N_{cave}' to 'N', symbol 'β' refers to ratio of L_{cave}' to 'L'.

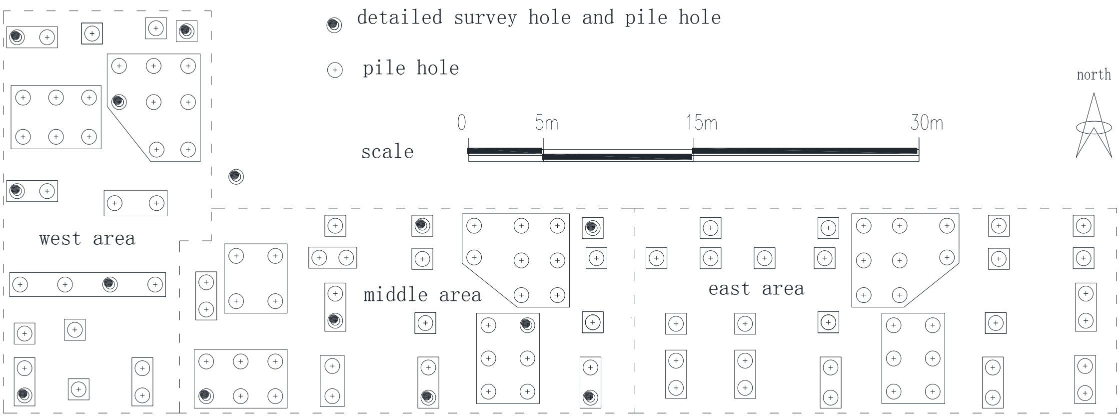

Fig.2. Floor plan for the pile foundation

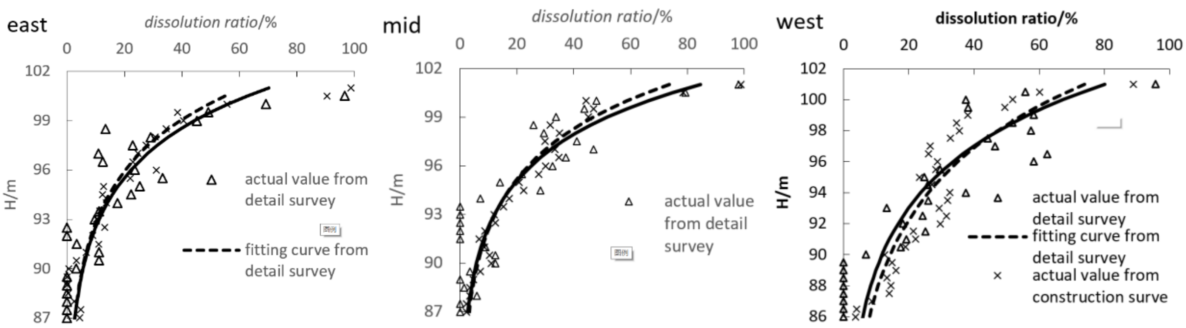

Fig.3. Depth distribution curve of the dissolution ratio

4.2 Data Processing

Based on detailed survey and construction survey data and with the proposed method, this paper obtains the theoretical rock embedding probability curve $P_{tx}(H)$ for detailed survey and the theoretical rock embedding probability curve $P_{ts}(H)$ for construction survey, respectively. According to the pile construction materials collected, the elevation distribution curve $P_D(H)$ of the actual rock embedding probability of pile holes is obtained.

Currently for the pile foundation project in karst terrain, the rock embedding depth of a survey hole is usually considered as the rock embedding depth of a pile hole. After the pile hole is excavated, the pile should be checked to ensure the whole section of the pile bottom is embedded into rocks. Therefore, the rock embedding curve $P_d(H)$ determined by the construction survey hole is the main basis for determination of whether the piles is embedded into rock in the engineering practice. The curve is obtained according to the construction survey data.

The curves $P_{tx}(H)$, $P_{ts}(H)$, $P_D(H)$ and $P_d(H)$ of the subareas at the site are shown in Figure 4. According to these curves and Formula (18), this paper obtains the theoretical rock embedding probability error curve for piles $\Delta P_{tx}(H)$ based on detailed survey data, the theoretical rock embedding probability error curve for piles $\Delta P_{ts}(H)$ based on construction survey data and the rock embedding probability error curve for construction survey holes $\Delta P_d(H)$ The results are shown in Figure 5.

$$\begin{cases} \Delta P_{tx}(H) = \left|P_{tx}(H) - P_D(H)\right| \\ \Delta P_{ts}(H) = \left|P_{ts}(H) - P_D(H)\right| \\ \Delta P_d(H) = \left|P_d(H) - P_D(H)\right| \end{cases} \tag{18}$$

The average rock embedding elevation $\bar{H}_{tx}$ for pile holes determined based on the theoretical rock embedding probability curve $P_{tx}(H)$ in detailed survey, the average rock embedding elevation $\bar{H}_{ts}$ for pile holes determined based on the theoretical rock embedding probability curve $P_{ts}(H)$ in construction survey and the average rock embedding elevation $\bar{H}_d$ for construction survey holes and the actual average rock embedding elevation $\bar{H}_D$ for pile holes are calculated according to the following formulas:

$$\begin{cases} \overline{H}_{tx} = \sum H_i \left[P_{tx}(H_i) - P_{tx}(H_i) \right] \\ \overline{H}_{ts} = \sum H_i \left[P_{ts}(H_i) - P_{ts}(H_i) \right] \\ \overline{H}_{d} = \sum H_i \left[P_{di}(H_i) - P_{d}(H_i) \right] \\ \overline{H}_{D} = \sum H_i \left[P_{D}(H_i) - P_{D}(H_i) \right] \end{cases} \tag{19}$$

where: Σ stands for the summation within the statistical elevation range; for the meanings of the other symbols, please refer to the preceding paragraphs.

The curve $P_{tx}(H)$ is not smooth. In order to reduce statistical errors, in Formula (18) and (19), the fitted expression of the curve is used as $P_{tx}(H)$, which is $P_{tx}(H)=AH^2+BH+C$.Before the fitting, some excessively large data are eliminated and the maximum value of $P_{tx}(H)$ is controlled slightly above 100%. The fitting results are shown in Table 2. The fitted curve is the dotted line in Figure 4. From Table 2 and Figure 4, it can be seen that, the fitting correlation coefficient R^2 is greater than 0.95. The fitted curve and the measured one are very close, indicating that the fitting result is good.

Tab.2. $P_{tx}(H)$ fitting result table

Area	Coefficient A	Coefficient B	Coefficient C	Correlation coefficient R^2
East	-1.1905	210.02	-9161	0.9666
Mid	-0.7378	126.46	-5316	0.9828
West	-0.5635	92.402	-3663.9	0.9690

The average rock embedding elevation error for pile holes under different methods are calculated according to the following formulas:

$$\begin{cases} \Delta\overline{H}_{tx} = \left| \overline{H}_{tx} - \overline{H}_{D} \right| \\ \Delta\overline{H}_{ts} = \left| \overline{H}_{ts} - \overline{H}_{D} \right| \\ \Delta\overline{H}_{d} = \left| \overline{H}_{d} - \overline{H}_{D} \right| \end{cases} \tag{20}$$

where $\Delta\overline{H}_{tx}$ is the error of the elevation $\overline{H}_{tx}$, $\Delta\overline{H}_{ts}$ is the error of the elevation $\overline{H}_{ts}$; $\Delta\overline{H}_{d}$ is the error of the elevation $\overline{H}_{d}$.

The calculation results of Formulas (19) and (20) are shown in Table 3.

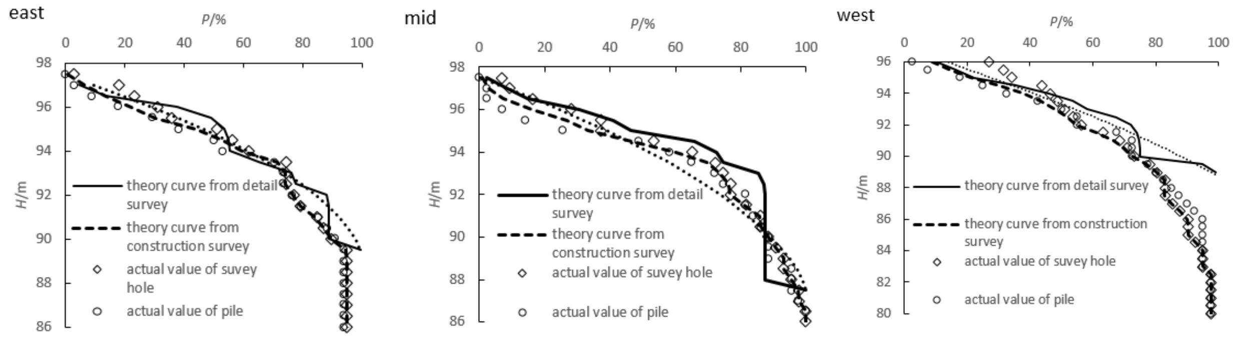

Fig.4. Rock embedding probability curves of pile groups

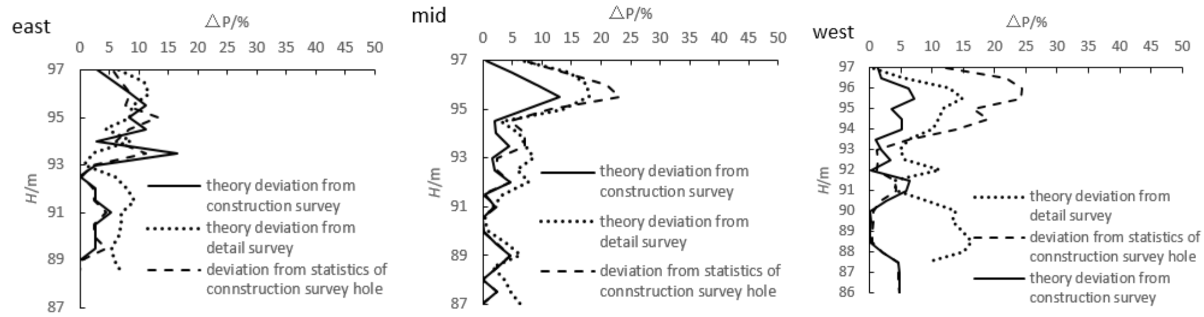

Fig.5. Rock embedding probability error curves of pile groups

Tab.3. Error analysis table for rock embedding probability model for pile holes

area	$\bar{H}_{tx}$	$\bar{H}_{ts}$	$\bar{H}_{d}$	$\bar{H}_{D}$	$\Delta\bar{H}_{tx}$	$\Delta\bar{H}_{ts}$	$\Delta\bar{H}_{d}$	$\Delta\bar{P}_{tx}$	$\Delta\bar{P}_{tx,\max}$	$\Delta\bar{P}_{ts}$	$\Delta\bar{P}_{ts,\max}$	$\Delta\bar{P}_{d}$	$\Delta\bar{P}_{d,\max}$
unit	m	m	m	m	m	m	m	%	%	%	%	%	%
east	94.20	93.84	94.12	93.45	0.75	0.39	0.67	6.93	11.62	1.70	6.68	5.54	15.00
mid	93.37	93.48	93.81	93.25	0.12	0.23	0.56	6.42	18.05	2.90	12.97	5.71	23.25
west	92.98	91.80	93.46	91.91	1.07	0.11	1.55	9.25	14.89	3.17	7.10	7.10	24.30

Note: in the table, $\Delta\bar{P}_{tx,max}$, $\Delta\bar{P}_{ts,max}$ and $\Delta\bar{P}_{d,max}$ are the maximum values of the error curves $\Delta P_{tx}(H)$, $\Delta P_{ts}(H)$ and $\Delta P_{d}(H)$, respectively. $\Delta\bar{P}_{tx}$, $\Delta\bar{P}_{ts}$ and $\Delta\bar{P}_{d}$ are the average values of the error curves $\Delta P_{tx}(H)$, $\Delta P_{ts}(H)$ and $\Delta P_{d}(H)$, respectively. for the meanings of the other symbols, please refer to the preceding paragraphs.

4.3 Results and Discussion

According to Table 3, Figure 4 and Figure 5, for the rock embedding probability curve for construction survey holes $P_d(H)$ obtained based on the construction survey data, the maximum error $\Delta\bar{P}_{d,max}$ is 15.00%~24.30%, the average error $\Delta\bar{P}_{d}$ is 5.54%~7.10%, and the average rock embedding elevation error $\Delta\bar{H}_{d}$ is 0.67m-1.55m. For the theoretical rock embedding probability curve for piles $P_{ts}(H)$ determined based on the probability model proposed in this paper according to the construction survey data at the site, the maximum error $\Delta\bar{P}_{ts,max}$ is 6.68%~12.97%, the average error $\Delta\bar{P}_{ts}$ is 1.70%~3.17%, and the average rock embedding elevation error $\Delta\bar{H}_{ts}$ is 0.11-0.39m. Though the curves $P_d(H)$ and $P_{ts}(H)$ are both obtained based on the construction survey data, the error of the curve $P_{ts}(H)$ is significantly smaller than that of the curve $P_d(H)$. The main reason is that: $P_{ts}(H)$ fully considers the effects of pile diameter and dissolution ratio on the actual embedment of piles into rocks, while $P_d(H)$ does not take these two factors into account. It can be inferred that, the greater the pile diameter is and the more complex the karst foundation conditions are at the site, the greater the error of $P_d(H)$ will be, but the error of the curve $P_{ts}(H)$ will be relatively stable. Accordingly, the embedment of pile groups into rocks revealed in the construction survey of piles will also deviate from the actual situation. The greater the pile diameter is and the higher the dissolution of the karst foundation is, the greater the deviation will be, which is an important reason why supplementary construction surveys are needed repeatedly on piles in the engineering practice. The pile group probability model proposed in this paper considers the effects of the pile diameter and the dissolution characteristics of the foundation on the embedment of pile groups into rocks, and can properly reflect the elevation distribution of rock embedding probability of pile groups at the site, so this model is truly advanced and rational.

According to Table 3, for the theoretical rock embedding probability curve $P_{tx}(H)$ in detailed survey determined based on detailed survey data, the maximum error $\Delta\bar{P}_{tx,max}$ is 11.62%~18.05%, the average error $\Delta\bar{P}_{tx}$ is 6.42%~9.25% and the average rock embedding elevation error $\Delta\bar{H}_{tx}$ is 0.12m-1.07m, which meet the accuracy requirements for the technical and economic feasibility study of the pile foundation scheme in engineering practice. As can be seen from Table 2, the curve $P_{tx}(H)$ is obtained based on very small amount of detailed survey. In each subarea, there are 8-9 holes drilled for detailed survey, and some of the boreholes are shared by adjacent areas, so there are only 21 boreholes in total at the site. The curve $P_d(H)$ is obtained based on the "one-pile-one-hole" construction survey data. There are 34-43 boreholes for construction survey in each subarea and 117 ones in total. This number is 5.6 times the previous number of holes, so it can be seen that the rock embedding probability analysis model for pile groups constructed in this paper can properly reflect the actual embedment of piles into rocks just by a small amount of survey work, which is very economic. More importantly, with the rock embedding probability model for pile groups constructed in this paper, it is possible to determine rock embedding elevations of piles at the site in the detailed survey stage, which can provide basis for the technical and economic evaluation of the pile foundation at the site.

From Table 3, it can be seen that, there will be a great error if the rock embedding depth of the construction survey hole is considered as that of the pile hole. The error $\Delta\bar{H}_d$ is 0.56-1.55m. If the rock embedding probability model for pile groups proposed in this paper are used for analysis based on the pile construction survey, the error $\Delta\bar{H}_{ts}$ of the rock embedding elevations of pile groups will only be 0.11-0.39m. Therefore, if the rock embedding probability model for pile groups proposed in this paper is applied in the pile construction survey stage, it is possible to accurately analyze the embedment of pile groups into rocks at the site and predict the average rock embedding elevation of the pile groups. This is of positive engineering significance to select reasonable construction method for piles and to finally determine rationality of the pile foundation.

According to Figure 3, due to the small number of holes in the detailed survey, the fitting correlation coefficient of the dissolution ratio is only 0.815~0.879, lower than 0.941~0.966 in the construction survey. Nonetheless, the depth distribution curves for dissolution ratio in the two periods are basically in coincidence after fitting, which indicates that the depth distribution curves of dissolution ratio generally have good numerical stability. This is an important guarantee for the numerical stability of the rock embedding probability model for pile groups.

Figure 4 shows that the curve $P_{tx}(H)$ is not smooth and involves significant skips or mutations, indicating that there are great statistical errors in the curve $P_{tx}(H)$ determined based on the detailed survey data of limited survey density drilling. The main reason for such errors is that: there is great uncertainty in the development of corrosion grooves and cave fissures. When the drilling density is low at the survey site, these karst forms are difficult to fully expose, leading to great certainty in the final survey holes; there are only a few boreholes in the detailed survey. To reduce the statistical errors of the curve $P_{tx}(H)$ determined based on detailed survey data, it is suggested that the curve be fitted with a function, which should be subject to the specific form of the curve. If the $P_{tx}(H)$ for each subarea of the site can be fitted into a parabolic form, the fitted curve will more properly reflect the actual embedment of pile groups into rocks than the original curve.

Conclusions

(1) In engineering practice, the embedment of construction survey holes into rocks is usually considered as the embedment of piles into the rocks, which does not consider the effects of the dissolution at the site and the pile diameter on to the embedment of pile groups into rocks; therefore, under many circumstances, there are great errors, prompting supplementary construction survey to be repeated in projects.

(2) The rock embedding probability model for pile groups takes into account the effects of pile diameter and dissolution characteristics of the site on the actual embedment of piles into rocks, and can properly reflect the elevation distribution features of rock embedding probability of pile groups at the site, so this model is truly advanced and rational.

(3) The pile group probability model proposed in this paper has good numerical stability. It

can help determine the average rock embedding elevation of pile groups at the site in the detailed survey stage, which meets the accuracy requirements for the technical and economic feasibility evaluation of the pile foundation in the design stage.

(4) If the rock embedding probability model for pile groups proposed in this paper is applied in the pile construction survey stage, it is possible to accurately analyze the embedment of pile groups into rocks at the site and predict the average rock embedding elevation of the pile groups. This is of positive engineering significance to the selection of pile foundation construction processes and the final determination of the rationality of pile foundation.

(5) When the drilling density in the site survey is small, the rock embedding probability curve for pile groups determined using the propose method may not be smooth, but a properly fitted curve can reduce its statistical errors.

(6) The pile group probability model is established based on site survey data with no extra test work needed; what is more, the data sources are cheap and abundant and the model is highly specific and operable, and thus it can be easily promoted and applied in engineering practice.

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