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Research Article

Prediction of Ultimate Antifloating Force of Bored Piles in Urban Road Crossing Overpass

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As an effective antifloating measurement in underpass engineering, uplift piles have been widely employed in the antifloating design of underground structures, such as basements, underground roads, and underground shopping malls. For the purpose of studying the antifloating behavior of bored piles and predicting the uplift bearing capacity in underpass engineering, the on-site pull-out tests of bored piles are carried out in laboratory. Besides, the MMF growth curve model, the ordinary hyperbolic model, and the exponential model are employed to fit and predict the ultimate bearing capacity of the measured uplift load and uplift displacement data of three test piles, respectively. The research results indicate that three test piles meet the stability requirements of antibuoyant bearing capacity, and the pull-up load-displacement curves of test piles are gentle and steep. Meanwhile, the fitting accuracy of the pull-displacement curve is high; specifically, the correlation coefficient is above 0.98619, and the average value is 0.99134, thereby verifying that the fitting effect of MMF growth curve model is better than those of the hyperbolic model and the exponential model. Therefore, the MMF growth curve model proposed in this paper not only describes the fitting of the uplift load-uplift displacement curve of uplift piles accurately but also predicts the ultimate bearing capacity of test piles. The research results provide an important reference for the antifloating behavior of bored piles in underpass engineering.

1. Introduction

The antifloating problem of underground engineering is related to the safety of the project. Serious consequences in underground engineering occur when it is not handled properly. In recent years, with the continuous expansion of the urban construction scale, the antifloating problem of underground structures becomes increasingly prominent. As an effective antifloating measure, uplift piles have been widely employed in the antifloating design of underground structures such as underground roads, underground shopping malls, and basements [1]. The uplift static load tests of a single pile are currently the most recognized method for determining the ultimate uplift bearing capacity in the engineering field. However, test piles are difficult to achieve the real failure state in engineering practice, due to the limitation of loading equipment, the influence of construction progress, and the requirements of test termination conditions. Therefore, the U - δ curve is incomplete, and the ultimate bearing capacity of a single pile cannot be obtained directly. In addition, because the uplift test is destructive, it is of great theoretical significance and practical engineering value to make use of the measured data and reasonably predict the ultimate bearing capacity of a single pile [2–4].

Therefore, scholars at home and abroad have put forward a number of methods for predicting pile bearing capacity through many experimental research and theoretical analysis. In most cases, a mathematical model needs to be selected to fit the static load U - δ curve to predict and analyze the limit state of the pile foundation. The accuracy of this prediction result is closely related with the fitting accuracy of the mathematical model, directly affecting the safety and economy of engineering design. At present, the commonly mathematical model prediction methods include hyperbolic model [5, 6], exponential model [7, 8], gray forecast model [9, 10], and growth curve model [11]. Liao and

Wang [12] studied the application of the MMF model in the prediction of foundation settlement and found that the MMF model reflects the whole process of the development of the foundation soil settlement with time under the condition of linear loading or approximately linear loading and predicts the foundation settlement accurately. Based on different types of single pile static load test data, Zhang and Yang [13] found that the fitting effect of the MMF model was significantly better than that of the ordinary hyperbolic model, the modified hyperbolic model, the complete exponential curve model, and the Gompertz model. The most common and important one is the hyperbolic model, but the fitting effect of the hyperbolic model is not ideal in some cases, especially in the plastic deformation stage [14]. Because of its good adaptability and strong fitting ability, the MMF growth curve model has been widely employed in the foundation settlement prediction [15] and the prediction of surface subsidence in goaf [16, 17]. However, the application of MMF growth curve model in pile foundation engineering is still rare, which is important to be researched systematically.

In this paper, the antifloating characteristics of pull-out piles in urban road crossing overpass are studied, and in situ static load test of a single pile is carried out in laboratory. By introducing the MMF growth curve model, exponential model, and hyperbolic model to fit the measured data of three piles, the variation law of ultimate bearing capacity of the uplift pile is discussed, and the load-displacement algorithm of a single pile is proposed. Finally, the ultimate uplift force of the uplift pile is predicted by introducing the fitting equation of the MMF growth curve model. The rationality and effectiveness of the method are illustrated by an engineering example.

2. MMF Growth Curve Model

The MMF model is a mathematical model to describe the growth process of things, which is proposed by Morgan-Mercer-Flodin in 1975. The growth rate of things in the whole growth process shows the common characteristics of slow-fast-slow [18]. The growth amount in the early stage is small, and it increases approximately linearly. In addition, it increases gradually over time and eventually stabilizes at a saturation value. The entire growth process is described in Figure 1.

According to the speed of growth or the change of the curvature of the curve, it is divided into three stages, which contains the initial growth stage, rapid growth stage, and stable growth stage, respectively. The expression of the MMF model is

$$y = \frac{ab + ct^d}{b + t^d}, \tag{1}$$

where y is the cumulative growth amount at time t, t is the time, a is the growth initial value parameter, b is the growth rate parameter, c is the growth saturation value, and d is the allometric growth parameter.

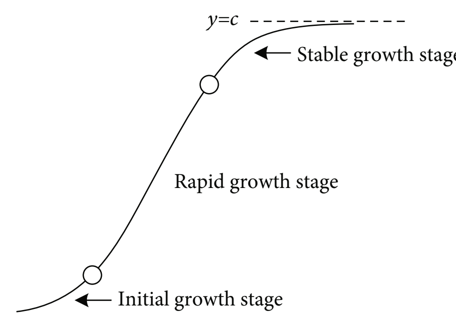


Figure 1: Sketch of MMF model curves.

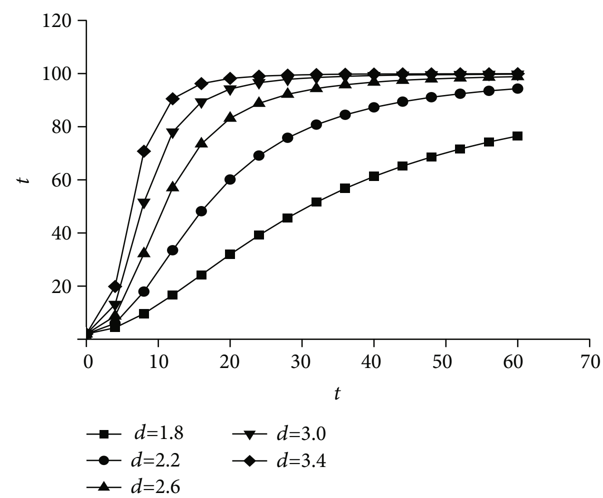


Figure 2: Flexibility of MMF model curves.

Besides, the MMF growth model has four main characteristics, which are shown as follows:

(1) The origin of the coordinates is not passed through. Specially, when $t = 0$ in Equation (1), and $y = a$. It is obvious that the model does not pass through the coordinate origin, and the parameters represent the initial growth

(2) Monotonicity. Specially, the function expression of growth rate is obtained by derivative of Equation (1) to the time t

$$dy = \frac{(c - a)bdt^{d-1}}{\left(b + t^d\right)^2} > 0. \tag{2}$$

It is obvious that the model is monotonically increasing.

(3) Boundedness. Specially, when t tends to infinity in Equation (1), the final cumulative growth value tends to be close to c

$$\lim_{t \longrightarrow \infty} y = c. \tag{3}$$

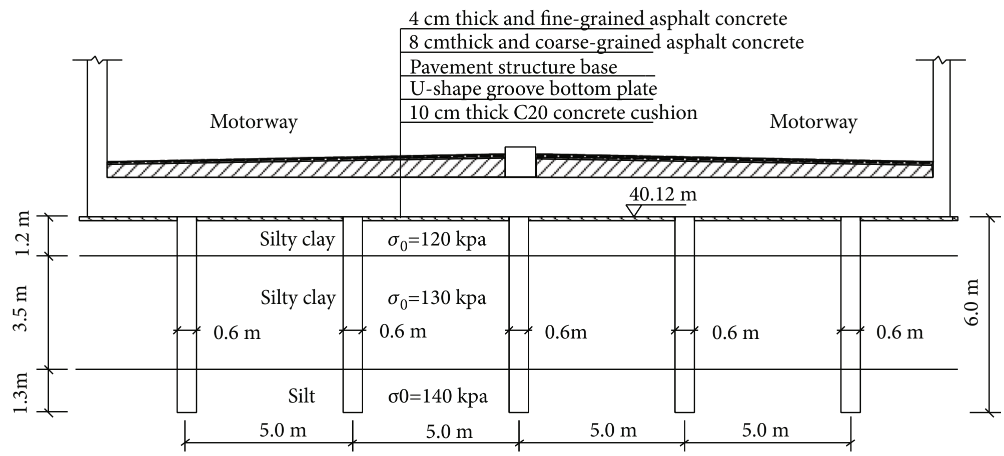


Figure 3: Profile of U-groove of motorway.

Table 1: Physical and mechanical parameters of ground strata.

Soil layer	Soil state	Soil layer thickness/m	Cohesive forces/KPa	Internal friction angle/°	Compression modulus/MPa	Basic allowable value of bearing capacity/KPa	The standard value of ultimate friction resistance of pile side soil/KPa
Filling soil	Hard plastic	1.4-2.5	24.9	18.9	None	None	None
Silty clay	Soft plastic	5.0-8.0	26.6	18.4	5.0	120	40
Silty clay	Plasticity	4.0-6.0	20.7	20	5.9	130	50
Silt	Medium density-dense, wet	3.0-5.0	30.4	18.7	6.5	140	60
Silty clay	Plasticity	4.0-6.0	23.4	20.5	6.6	140	60

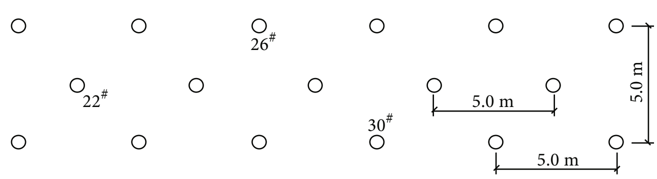


Figure 4: Layout plan of test piles.

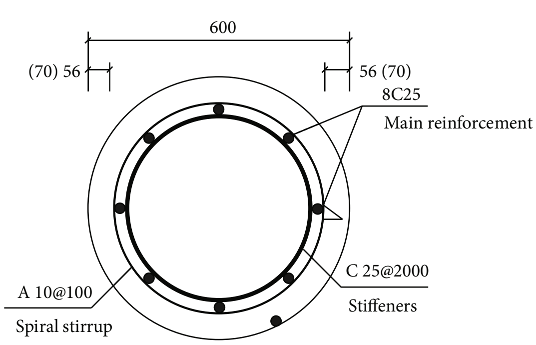


Figure 5: Pile section reinforcement drawing.

Figure 6: Field vertical pulling test.

(4) Plasticity. Specially, for the same parameters *a*, *b*, and *c*, when $a = 2$, $b = 500$, and $c = 100$, the effect of the change of parameter *d* on the shape of the MMF growth curve is shown in Figure 2. It is obvious that it has a strong fitting ability

Based on the fact that the U - δ curve of the uplift pile is a growth curve, which has the characteristics of nonlinear monotonic increase and boundedness, the MMF growth curve model is employed to fit the U - δ curve of single pile

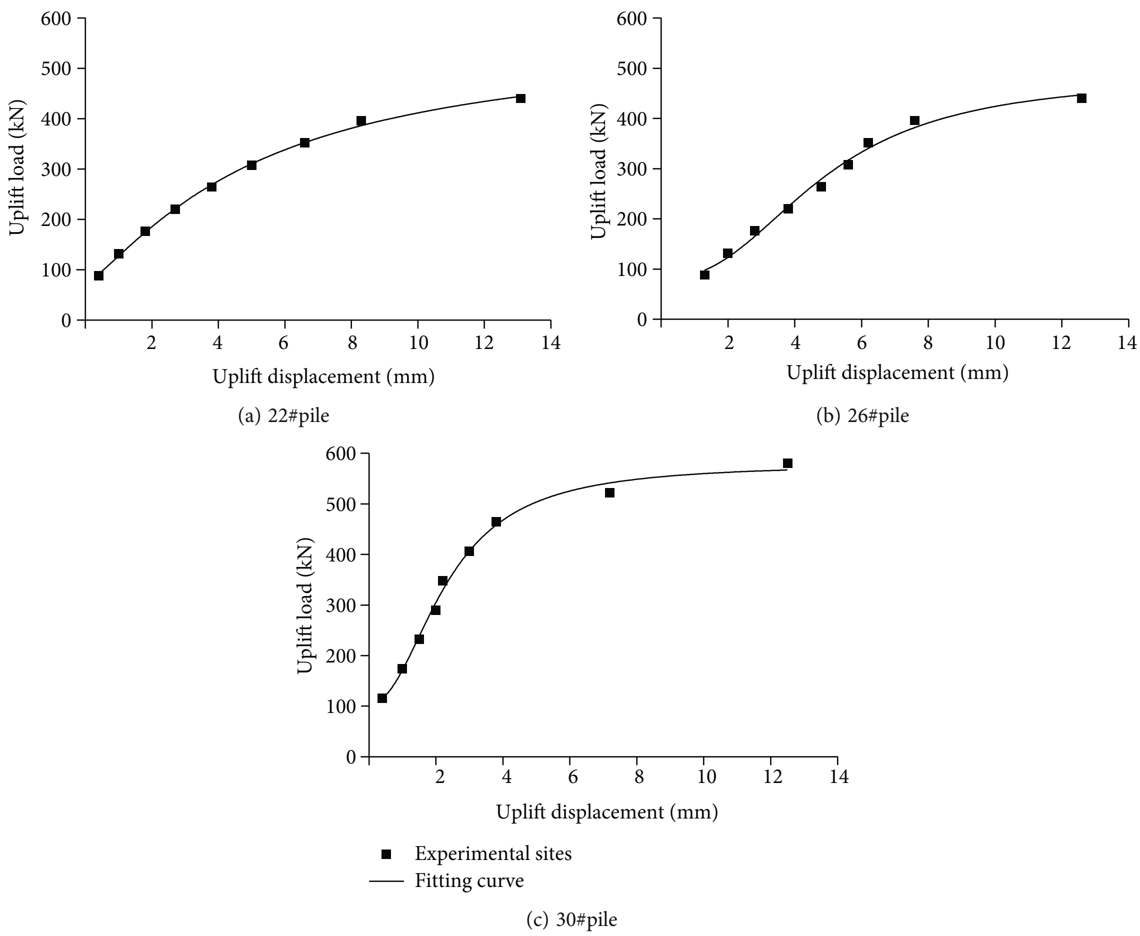


Figure 7: Fitting effect of MMF model.

uplift static load and predict the ultimate uplift resistance. The uplift pile sets the pile top load U as the dependent variable and regards the pile top uplift δ as a generalized time, and sets $a = P_1$, $b = P_2$, $c = P_3$, and $d = P_4$, then the U is obtained.

$$U = \frac{p_1 p_2 + p_3 \delta^{p_4}}{p_2 + \delta^{p_4}}, \tag{4}$$

where U is the uplift load of the uplift pile, δ is the uplift displacement of the uplift pile, P_1 is the initial value of the uplift load, P_2 is the increase rate parameter of the uplift load, P_3 is the progressive limit load value of the uplift pile, and P_4 is a parameter related to the shape of the fitting curve.

The steps of the MMF growth curve model to solve the ultimate pull-out bearing capacity of a single pile are obtained as follows,

(1) The U-δ curve is arranged, according to the measured data

(2) The parameter values P_1, P_2, P_3, and P_4 are obtained, according to the fitting U-δ curve of the test pile drawn in Equation (4)

(3) Substituting the obtained parameters into Equation (4), and setting $\delta \longrightarrow \infty$, the ultimate bearing capacity $U = P_3$ of a single pile is obtained

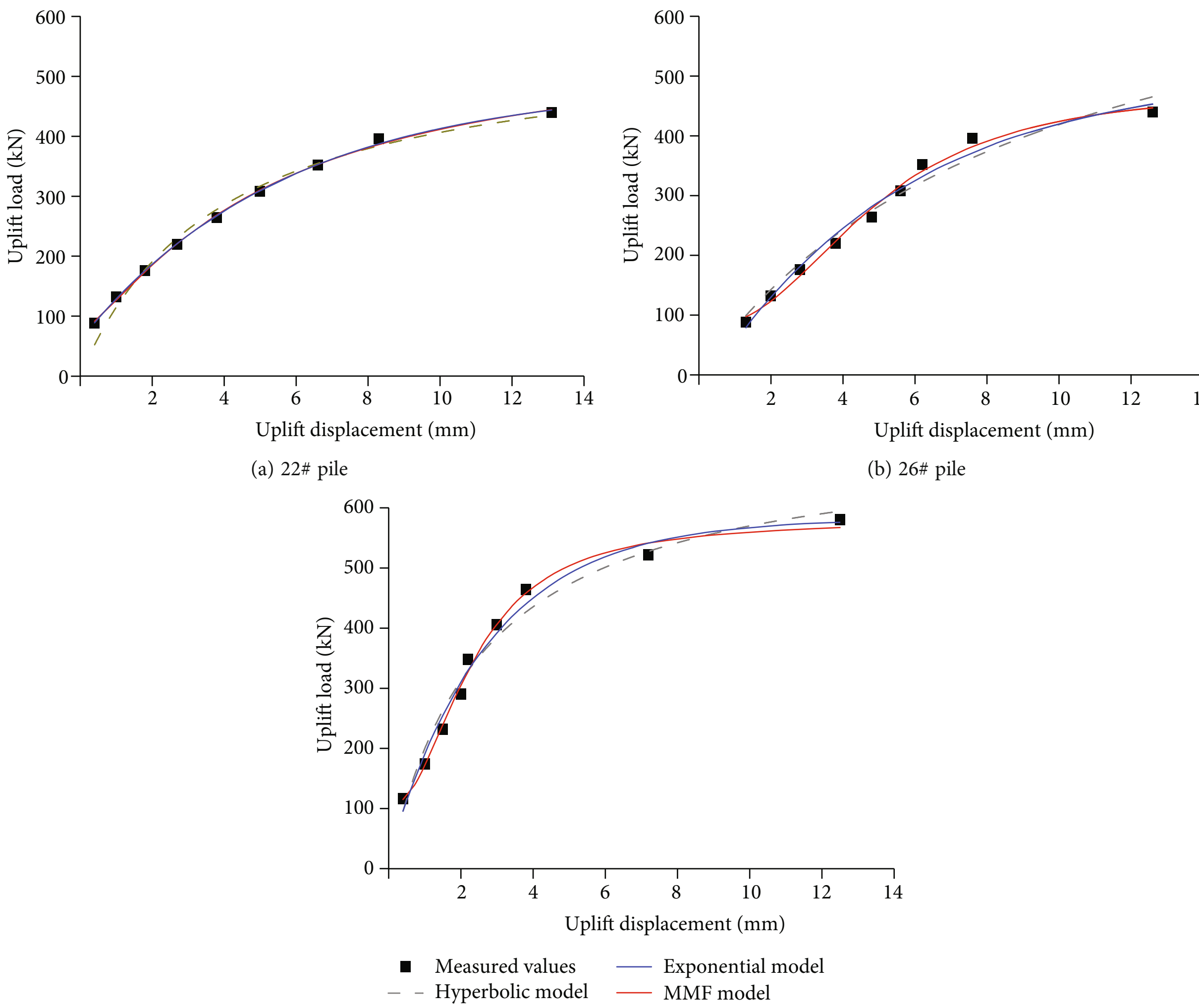
3. Field Test of Uplift Piles

3.1. Engineering and Geology Overview. This project is an urban main road underpass railway overpassing project in Zhoukou city, and the road cutting adopts a closed U-shaped groove structure. The cross-sectional view of the U-shaped groove in the section AK0 + 280~AK0 + 320 of the motorway is shown in Figure 3.

To meet the requirement of structural antifloating stability, the U-shaped groove structure adopts uplift piles to resist the buoyancy of groundwater, and the starting and ending mileage of the piles is AK0 + 180.00~AK0 + 600.00. The engineering landform belongs to the flat and open alluvial plain, and the location layer is mainly the fourth series of new systems and the upper updated system. The groundwater in the study area is Quaternary pore water, which mainly occurs in the silty clay and silt layers of the Quaternary. The groundwater table is at a depth of 1.50 m to 2.00 m. Besides, the physical and mechanical parameters of the rock and soil layers are listed in Table 1.

Table 2: Ultimate bearing capacity forecasted for piles.

Test pile number	Fitting equation	R	U_{max}/kN	U_s/kN
22#	$U = \dfrac{72.7552 \times 7.99628 + 561.349\delta^{1.2574}}{7.99628 + \delta^{1.2574}}$	0.99747	561.34900	440
26#	$U = \dfrac{82.29907 \times 47.50962 + 482.68323\delta^{2.4422}}{47.50962 + \delta^{2.4422}}$	0.98619	482.68323	440
30#	$U = \dfrac{104.6301 \times 6.11459 + 579.07119\delta^{2.15928}}{6.11459 + \delta^{2.15928}}$	0.99037	579.07119	580



(a) 22# pile (b) 26# pile (c) 30# pile

Figure 8: Comparison of MMF model with hyperbolic model and exponential model.

3.2. The General Situation of Pile Foundation Trial. Eight uplift piles are tested in the field test, which are drilling cast-in-place piles. Before the static load test, the test pile is tested under low strain, and the pile body is complete, which is the type I pile. In this paper, three typical roots (22#, 26#, and 30#) are selected as representatives. The layout plan of the test pile and the reinforcement drawing of the pile section (the values in brackets apply to 8 m uplift piles) are shown in Figures 4 and 5, respectively.

The strength grade of pile concrete is C30, and the diameter of the pile is 600 mm. 22# and 26# piles are 6 m long, and the design value of bearing capacity is 220 kN. The length of 30# pile is 8 m, and the design value of bearing capacity is 290 kN. According to the field conditions, the counterforce device for natural foundation beams is introduced in the test. The counterforce device consists of beams, steel caps, buttresses, and welded steel bars. The loading device consists of an oil jack, hoses, an oil pump, and an

Table 3: Comparison of the fitting effect.

Test pile number	δ/mm	U /kN				Error/mm		
		Measured values	Hyperbolic model	Exponential model	MMF model	Hyperbolic model	Exponential model	MMF model
22#	0.40	88.00	52.19	88.94	91.33	-35.81	0.94	3.33
	1.00	132.00	114.68	128.78	127.07	-17.32	-3.22	-4.93
	1.80	176.00	177.73	175.74	174.15	1.73	-0.26	-1.85
	2.70	220.00	230.53	221.24	221.11	10.53	1.24	1.11
	3.80	264.00	278.43	267.89	268.79	14.43	3.89	4.79
	5.00	308.00	317.26	309.47	310.30	9.26	1.47	2.30
	6.60	352.00	355.30	352.86	352.69	3.30	0.86	0.69
	8.30	396.00	384.83	387.35	386.20	-11.17	-8.65	-9.80
	13.10	440.00	436.43	443.72	444.37	-3.57	3.72	4.37
26#	1.30	88.00	98.87	78.68	97.68	10.87	-9.32	9.68
	2.00	132.00	142.76	130.16	123.40	10.76	-1.84	-8.60
	2.80	176.00	186.74	181.47	164.96	10.74	5.47	11.04
	3.80	220.00	234.22	235.88	224.12	14.22	15.88	4.12
	4.80	264.00	275.01	281.20	279.48	11.01	17.20	15.48
	5.60	308.00	303.72	311.94	316.82	-4.28	3.94	8.82
	6.20	352.00	323.32	332.21	340.35	-28.68	-19.79	11.65
	7.60	396.00	363.67	371.69	382.11	-32.33	-24.31	13.89
	12.60	440.00	465.84	452.76	447.08	25.84	12.76	7.08
30#	0.40	116.00	96.02	95.46	115.12	-19.98	-20.54	-0.88
	1.00	174.00	200.00	190.79	171.32	26.00	16.79	-2.68
	1.50	232.00	263.39	255.81	238.36	31.39	23.81	6.36
	2.00	290.00	312.99	310.03	304.91	22.99	20.03	14.91
	2.20	348.00	329.93	329.10	329.03	-18.07	-18.90	18.97
	3.00	406.00	385.60	392.94	406.76	-20.40	-13.06	0.76
	3.80	464.00	427.35	440.67	458.07	-36.65	-23.33	-5.93
	7.20	522.00	528.71	541.03	541.45	6.71	19.03	19.45
	12.50	580.00	595.66	576.17	566.97	15.66	-3.83	13.03

automatic loading instrument. In the test, the displacement sensor is installed at the top of the pile to measure the uplift of the pile. The maximum uplift load applied in the test is twice the characteristic value of a single pile load capacity. Three test piles are loaded in steps with equal amounts. The incremental loading is 1/10 of the design bearing capacity, and the first increment is 1/5 of the design limit. Based on the slow maintenance loading method, and the criteria for loading stability and the conditions for termination of loading are in accordance with JGJ 106-2014 "Technical code for testing foundation piles for buildings." The field survey of vertical uplift static load test of the single pile is shown in Figure 6.

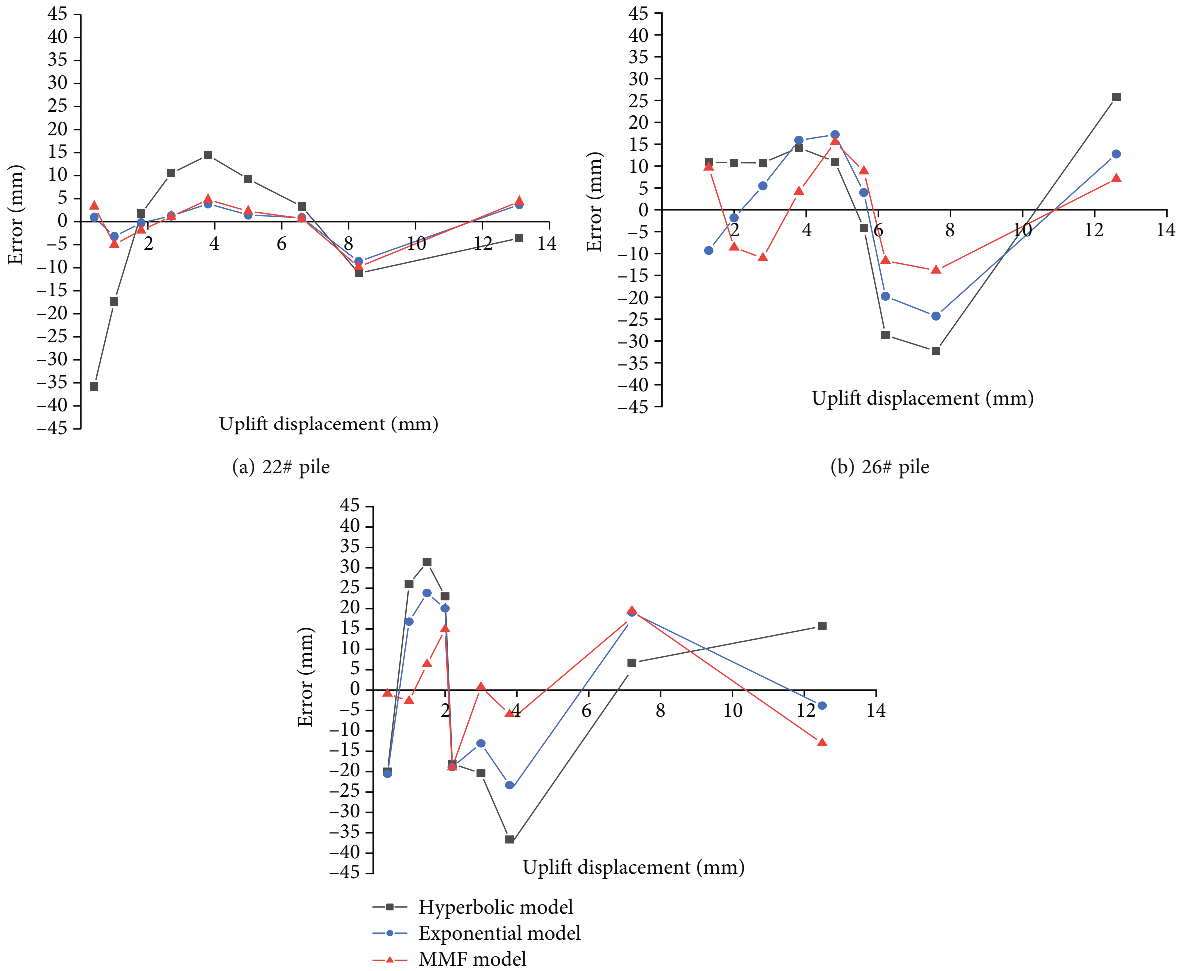
4. MMF Model Fitting Curve of Uplift Pile and Bearing Capacity Prediction

Based on the data of uplift load and uplift displacement of three uplift piles measured in the field, the model MMF is employed to fit the data, and the fitting effect is shown in Figure 7. The predicted curve is in agreement with the measured data accurately. The equation of the fitting curve for each pile, the estimated bearing capacity U_{max}, the design bearing capacity U_s, and the correlation coefficient R are shown in Table 2.

Table 4: The error sum of squares of the results predicted by the three models.

Test pile number	Hyperbolic model	Exponential model	MMF model
22#	2612.75	422.23	408.76
26#	3280.47	2071.57	1245.04
30#	5033.56	3246.23	1339.92

The average value of the correlation coefficient R is 0.99134. For the two types of U-δ curves applicable to the cast iron antilift pile, the MMF model exhibits high fitting accuracy, which reflects the plasticity of the mathematical model MMF model accurately. Therefore, the mathematical model MMF is suitable for predicting the ultimate uplift safety of the pile.



(a) 22# pile

(b) 26# pile

(c) 30# pile

Figure 9: Error comparison chart of MMF model, hyperbolic model, and exponential model.

5. Comparison of MMF Model, Exponential Model, and Hyperbolic Model

The hyperbolic model is widely employed to predict the bearing capacity of piles because of its simplicity and applicability. To analyze the fitting accuracy of the MMF model, the exponential model, and the hyperbolic model, the static load data of three piles are fitted with the hyperbolic model, the exponential model, and the MMF model, respectively, and the fitting errors are also calculated. The results are shown in Figure 8 and Table 3.

It is obvious that the fitting error of the MMF model is generally smaller than those of other two models, and the hyperbolic model has a large fitting error in the initial region of the U-δ curve. The fitting efficiency of the MMF model is better than those of the hyperbolic model and the exponential model. Through calculation, the error sum of squares of the results by three models is shown in Table 4.

In conjunction with Figure 9 and the sum of squares of the error table, it is obvious that the prediction results of the exponential model are better than those of the hyperbolic model, but the error of the MMF model is lower than those of the exponential model and the hyperbolic model.

6. Conclusions

The precise perdition on the ultimate bearing capacity of uplift piles is important in engineering, because the reasonable and effective monitoring accelerates the construction process and makes response to disasters in time. However, it is affected by complex factors. In this paper, the MMF model is employed to fit the U-δ curves of three bored piles and to predict the ultimate bearing capacity. The research results are obtained as follows.

(1) The on-site pull-out tests are carried out on three bored piles in urban road crossing overpass of Zhoukou city. The pull-out load test results show that the antifloating bearing capacity of piles completely meets engineering requirements

(2) With regard to the fitting degree of load-displacement curves, the MMF model is better than the hyperbolic

model and exponential model, and correlation coefficients are 0.96827~0.97898, 0.97901~0.99863, and 0.98619~0.99747, respectively. Besides, the average correlation coefficients are 0.97305, 0.98567, and 0.99134, respectively

(3) The MMF model is suitable to describe the antifloating behaviour of bored piles and predict the ultimate bearing capacity. The reliability of MMF model in the ultimate antifloating bearing capacity is verified in engineering application

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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