Application Research on Transient Rayleigh Technology in Pile Foundation Detection

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Abstract—Detection of pile foundation is one of the most important procedures in the evaluation of pile bearing capacity and pile quality. In this paper, the application of the transient Rayleigh technology in detection of pile foundation (pile integrity, pile verticality and pile bearing capacity) have been illustrated by few examples. By using transient Rayleigh technology, the shear wave velocity of soil around pile can be tested. The pile integrity, the pile verticality and the pile bearing capacity can also be detected rapidly. Comparing with the static load test and others dynamic technologies, this method is more economical and nondestructive.

Keywords—*transient rayleigh technology; pile foundation detection; pile bearing capacity ; share wave velocity; pile integrity ; pile verticality*

I. INTRODUCTION

As one of the most commonly used foundation forms, pile foundation is an concealed structure. The quality of pile foundation is directly related to the operation and safety of the main structure. Once an accident happens in pile foundation, the reinforcement treatment is very difficult. Pile testing is an important measure to conduct a comprehensive evaluation on the pile bearing capacity and the pile quality.

At present, the main technologies used in pile foundation detection include: the direct methods such as static load test, drill core test, and indirect methods such as high strain method, low strain method, sound wave transmission method, etc. Static load test is more effective but it takes a long time and large investment, and in some cases it is difficult to achieve. Dynamic measurement technology has been applied widely, but it is very sophisticated to interpret in theoretical basis and testing technology and application, and needs further research.

Developed in the 1990' s, transient Rayleigh wave exploration technique is a new engineering and environmental geophysical method. By using the dispersion characteristics of Rayleigh wave and the relativity between wave velocity and physical mechanical character of site soil, many geological engineering problems could be solved. During the process of pile testing, transient Rayleigh wave technology could also play a very significant role.

II. THEORY OF TRANSIENT RAYLEIGH WAVE TECHNOLOGY

Surface waves are divided into Rayleigh and Love wave. Rayleigh wave has the strongest energy, the maximum amplitude, and the minimum frequency, making it easy to identify and measure.

The essence of transient Rayleigh exploration method is basing on the measurement of velocity of different frequency of Rayleigh wave to infer the rock and soil properties of the different depth (distance). During the detection process, an instantaneous impact force is exerted on the ground, and the Rayleigh waves with certain frequency range will be produced. The Rayleigh waves with different frequency will be superimposed together, and propagate forward in the form of pulse. Along the direction of wave propagation, N+1 detectors (12 or 24) are set in Δx interval, propagation characteristics of the Rayleigh wave of N*Δx length range could be tested. With the spectrum analysis, Rayleigh wave in each frequency can be isolated and one or more dispersion curves could be calculated. This multichannel superposition method could eliminate the random interference signal, and the geologic bodies in the dispersion curve reflects more prominent. This method has advantages of high construction efficiency, portable equipment and low cost. The factors that influenced the accuracy of longitudinal wave velocity and shear wave velocity are the extraction of Rayleigh wave, the computation of dispersion curves, and the inversion calculation of the longitudinal and shear wave velocity.

At present, f-k transform is widely used. The procedure is real amplitude recovery-spectrum analysis-1-D filtering-f-k transform-dispersion curves-interval velocity inversion. This method requires at least six common shot records to obtain a dispersion curve. The obtained dispersion curve is the weighted average level of the whole array length along horizontal direction. This method reduces the vertical and lateral resolution of Rayleigh wave, and some small local anomalies could not be detected. It is difficult to meet the accuracy requirements of detection.

To solve this problem, Professor Jiangping Liu proposed the adjacent-channel transient Rayleigh wave method that uses $\tau - p$ transform to extract the Rayleigh wave. The procedure is true amplitude recovery-spectrum analysis- $\tau - p$ filtering -

Rayleigh wave extraction-calculation of dispersion curve of neighboring traces-interval velocity inversion. This method could eliminate the average effect and improve the vertical and lateral resolution of Rayleigh wave. It broaden the scope of application of transient Rayleigh wave method. Transient Rayleigh wave technology in pile foundation detection process can be used for pile integrity testing, pile verticality detection and single pile bearing force detection.

III. APPLICATION OF TRANSIENT RAYLEIGH WAVE TECHNOLOGY IN THE DETECTION OF PILE FOUNDATION

A. Pile Integrity Detection

Pile integrity refers to the pile conditions such as defects of segregation, necking, pile breaking, sediment in pile tip, and pile head laitance. It is a comprehensive qualitative index that could reflect the relative change of pile size, material compactness and continuity of the pile, which is classified by the effects on the bearing capacity of pile. Powder jet pile foundation is used widely in expressway construction. There is a direct drilling on soft soil foundation and the cement powder is evenly sprayed into the loose soil, which forms a semi rigid pile. It could reinforce foundation and prevent significant subsidence. Because its construction process is completed underground, making the detection of their quality is very difficult. The existing methods failed to achieve the purpose of construction quality control, therefore, the detection problem has been the "black box" problem.

Professor Jiangping Liu used the adjacent-channel transient Rayleigh wave method to detect the quality of cement injection pile. Wenxia Ding used this method to detect the quality of cement mixing pile. This technology improves the nondestructive detection precision, resolution, and detection efficiency. Mathematical models between velocity and physical properties have been bulit, and physical properties of pile could be obtained.

This method has following advantages: (1) The length, integrity and verticality of pile could be presented visually; (2) Without disturbing or damaging of the pile, the visual color classification of intensity could be obtained by quantitative processing of the wave velocity; (3) The broken piles and the strength of the weaker parts can be found in early stage; (4) Comparing with the static load test, the bearing capacity of the pile can be estimated; (5)The cost of testing can be reduced and the detection rate can be improved greatly.

B. Pile Verticality Detection

In ordinary industrial and civil construction, pile is generally designed to be a vertical pile. Nevertheless, the extrusion during construction, overload of bottom face in some area, horizontal displacement of supporting structure of foundation pit would lead to the deviation of pile and pile tilt. The stake inclination makes the pile under eccentric compression, reduces the bearing capacity, and breaks the pile. Therefore, the allowable deviation of pile verticality could not exceed 1% which is clearly stipulated in Code for Acceptance of Construction Quality of Building Foundation (GB50202-2002).
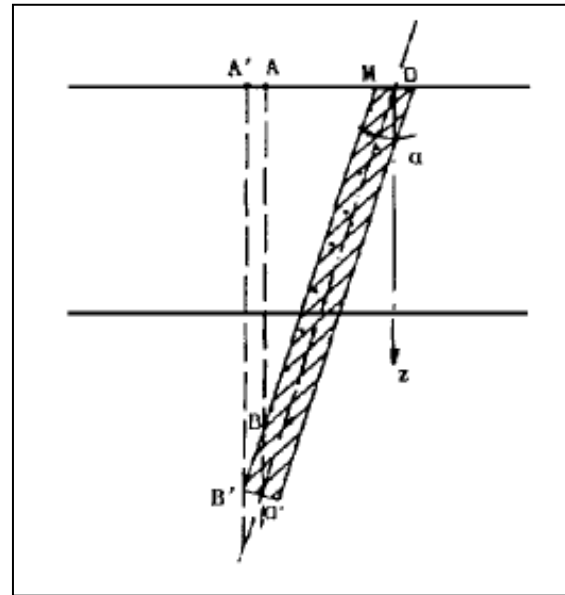

Fig. 1. Diagram of Detection Principle

The existing detection techniques of pile verticality is not very effectual, and the pile verticality detection has been a difficult problem in engineering field. With the progress of the detection technique of pile foundation , it is possible to test the actual verticality and angle of inclination of pile. Professor Yanhui Li put forward the method that uses Rayleigh wave to detect pile verticality based on the frequency dispersion of Rayleigh wave in the layered medium.

The dispersion curve tested by Rayleigh wave has an internal relation with underground medium structure. The stratigraphic structure within a certain depth of the ground can be received by inversion interpretation of dispersion curves. Since the propagation velocity of the Rayleigh wave in concrete is far greater than the propagation velocity of soil in surrounding soil, and the concrete density is higher than that of the surrounding soil density, it is easy to identify the interfaces of soil and concrete and to receive the interface burying depth of concrete. So the angle between pile and XOZ face could be calculated as :

$$\alpha_y = \tan^{-1}\frac{MA}{AB}$$
(1)

α_x can also be calculated. Using the formula: $\cos^2\alpha_z + \cos^2\alpha_x + \cos^2\alpha_y = 2$, α_z could be derived. So the angle of inclination of pile is:

$$\alpha = \frac{\pi}{2} - \alpha_z$$
(2)

By using this kind of test technology, a manual hole digging pile of high residence building was tested, and good results was achieved.

C. Pile Bearing Capacity Detection

Bearing capacity of single pile refers to the maximum external load that pile foundation could bear without stability failure and excessive settlement. There are many detection technologies which could be divided into two categories: direct

method and indirect method. The stress of pile in static load test is close to its actual working condition, so the result is relatively reliable. But there are many deficiencies in test equipment, test efficiency, working conditions or expenses.

The author proposed an indirect method that Rayleigh wave was used to detect the bearing capacity of single pile. The model between shear wave velocity v_s and pile side resistance q_{sik} and the model between shear wave velocity v_s and pile tip resistance q_{pk} could be obtained through SPT blow count $N_{63.5}$. And the bearing capacity of single pile could be determined.

The relation between $N_{63.5}$ and q_{sik} and the relation between $N_{63.5}$ and q_{pk} could be derived using the hyperbolic function models (3). The asymptote of the formula could determine the limit value of soil strength. It not only considers the nonlinear characteristics of soil strength, but also reflects the limit value of the strength of the different soil types.

$$q_{sik}, q_{pk} = a th(N_{63.5}/b + c) \tag{3}$$

Equation (3), a, b, and c are undetermined coefficients, and could be determined by detection data of a lot of test piles.

$N_{63.5}$ and v_s could all reflect the soft and hard degree of soil layer, and the model between them could use exponential function ($v_s = a N_{63.5}^b$). Considering the complexity of the region and classification of soil, the models from different soil properties of three different regions were chosen, and the models between v_s and q_{sik} and the models between v_s and q_{pk} have been built as:

$$q_{sik}, q_{pk} = A th (B \lg v_s + C) \tag{4}$$

With bored pile, for example, the A, B, and C value were shown in Tab. I . Once a pile is detected, the first step is to categorize the soil around the pile according to different soil property, the second step is to use the Rayleigh wave method to test the shear wave velocity of each layer, and the final step is to calculate q_{sik} and q_{pk} of each layer and determine the bearing capacity of single pile.

The pile foundation of one high-rise building was tested by this technology. By using the Model I , the result (Tab. II) showed that the ratio of calculated and static load results was between 0.7625 to 1.0072, the average value was 0.8868, and

the standard deviation was 0.0942. By using the Model II , the ratio of calculated and static load results was between 0.7562 to 1.0111, the average value was 0.8784, and the standard deviation was 0.0910; By using the Model III, the ratio of calculated and static load results was between 0.7413 to 0.9874, the average value was 0.8680, and the standard deviation was 0.0920. The results are secure and the accuracy of using the transient Rayleigh wave to test the bearing capacity of single pile is relatively high.

IV. CONCLUSION

Using the transient Rayleigh wave detection technology to test pile foundation (including pile integrity, pile verticality, and bearing capacity of single pile) have obvious advantages: (1) The length and integrity of pile can be tested without disturbing and destroying the pile body; (2) The verticality and pile inclination angle of pile body can be rapid detected ; (3) The bearing capacity of single pile could be estimated. This technology could reduce the cost, improve the efficiency, and have no damage. But more research works aiming at different regions, different type of soil, different type of pile should be done in future.

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TABLE I.   A, B, C VALUE OF BORED PILE

Soil Property		Model Ⅰ			Model Ⅱ			Model Ⅲ		
		A	B	C	A	B	C	A	B	C
q_{sik}	Clay Soil	98	1.0089	-1.8475	98	1.4269	-2.8162	98	1.2512	-2.4525
	Brown Clay	70	1.0089	-1.8475	70	1.4269	-2.8162	70	1.2512	-2.4525
	Fine Sand	80	1.1148	-2.1139	80	0.8333	-1.4629	80	1.001	-1.8350
	Medium Sand	90	1.1148	-2.1139	90	0.8333	-1.4629	90	1.001	-1.8350
	Coarse Sand	116	1.1148	-2.1139	116	0.8333	-1.4629	116	1.001	-1.8350
	Gravel Sand	135	1.1148	-2.1139	135	0.8333	-1.4629	135	1.001	-1.8350
q_{pk}	Clay Soil	1600	0.9685	-1.9216	1600	1.3699	-2.8515	1600	1.2012	-2.5024
	Fine Silty Sand	1100	1.3387	-2.6707	1100	1	-1.8895	1100	1.2012	-2.3360
	Fine Sand	1500	1.3387	-2.6707	1500	1	-1.8895	1500	1.2012	-2.3360
	Medium Sand	1900	1.3387	-2.6707	1900	1	-1.8895	1900	1.2012	-2.3360
	Coarse Sand	2500	1.3387	-2.6707	2500	1	-1.8895	2500	1.2012	-2.3360
	Gravel Sand	2500	1.3387	-2.6707	2500	1	-1.8895	2500	1.2012	-2.3360

TABLE II.   COMPARISON RESULTS OF TRANSIENT RAYLEIGH WAVE METHOD AND STATIC LOAD TEST

No.	Length/m	Static Load Test /kN	Model Ⅰ		Model Ⅱ		Model Ⅲ	
			Q_{uk}/kN	α_1	Q_{uk}/kN	α_2	Q_{uk}/kN	α_3
1	28.9	3300	3256.35	0.9868	3148.42	0.9541	3165.80	0.9593
3	33.5	4200	3711.40	0.8837	3643.40	0.8675	3650.99	0.8693
4	28.9	3600	2745.06	0.7625	2722.25	0.7562	2668.69	0.7413
5	33.5	3300	3323.89	1.0072	3336.78	1.0111	3258.36	0.9874
6	28.9	3300	2787.6	0.8447	2806.63	0.8505	2737.85	0.8296
7	33.5	3900	3259.22	0.8357	3241.72	0.8312	3201.33	0.8208