Load Transfer Law and Influence Factors of Piles in Deep Loess Area

Lixiang Cao\textsuperscript{1,2*}, Ting Du\textsuperscript{1,2}, Tiecheng Yan\textsuperscript{1,2}, Liping Liu\textsuperscript{1,2} and Xinyao He\textsuperscript{3}

\textsuperscript{1}College of Civil Engineering, Longdong University, Qingyang, Gansu, 745000, China
\textsuperscript{2}Provincial Key Laboratory of Loess Engineering Properties and Application in Universities, Qingyang, Gansu, 745000, China
\textsuperscript{3}Law School, Longdong University, Qingyang, Gansu, 745000, China
\textsuperscript{*}Corresponding author’s e-mail: 56288028@qq.com

Abstract. This paper summarizes the characteristic of four kinds composite foundation - compacted concrete composite foundation, Lanzhou loess foundation, highway soft soil foundation, just - soft pile composite foundation. Based on load tests and pile stress analysis of the measured data, summarizes the four foundation pile load characteristics and load transfer mechanism. The factors that influence the pile load transfer law are those: the pile tip soil properties, Pile shaft stiffness and length to diameter ratio, cement mixing ratio, Soil types, Moisture content, Compactness, The use of mattress layer.

1. Introduction

The research on the load transfer law of piles has always been placed in an important position in geotechnical engineering and underground engineering. Lots of domestic and foreign scholars have conducted in-depth research and achieved numerous results\cite{5-14}. Duan Ji-wei studied the load transfer law of cement mixing pile through full-scale field test. The results show that the load transmitted to the end of the pile accounts for a very small proportion of the load on the top. The deformation, axial force and side friction of piles are mainly concentrated in the depth of 0-\textit{l}_c (critical pile length) When the external load increases, the deformation of the pile will increase in the depth of 0-\textit{l}_c, but when the depth is greater than \textit{l}_c. The deformation of the pile, the axial force of the pile and the side friction resistance change less with the increase of the external load. The failure of cement mixing pile occurs in the shallow layer, and the failure mode is circular tension crack or pile crushing. In the elastic range, the finite element calculation value of pile stress is consistent with the measured value\cite{15}. The author refers to some relevant literature, summarizes the load transfer law of different kinds of piles under different geological conditions, several factors affecting the load transfer law of piles and the treatment methods adopted for the affecting factors. This paper mainly introduces four kinds of foundations: tamped concrete composite foundation, loess foundation in Lanzhou area, soft soil foundation of expressway, rigid -flexible pile composite foundation.

2. Factors affecting the load transfer of piles

For the deep soft soil foundation, it is found that the main factors affecting the settlement of the foundation and the load distribution of the pile-soil of the composite foundation are the pile length and
the pile spacing[1]. For rammed cement soil pile composite foundation, the main affecting factors are the material strength of pile shaft, the length of pile shaft and the cement mixing ratio[2]. Zhang Shihua and Ma An-gang studied the test results of the axial force of pile in the pile foundation test of a substation project in Lanzhou[3], through the analysis of the distribution of the resistance to compression and pull-out friction and the resistance at the pile end, the transfer law of the load of the large-diameter bored pile in the saturated loess field was obtained. The main factors that affect the friction of soil around the pile are soil type, compactness and moisture content, the difference of moisture content is the main reason for the difference of ultimate friction between the upper part and the lower part of the pile, the different hole forming technology also directly affects the load transfer law of the pile. For rigid flexible pile composite foundation, the presence or absence of a cushion is an important factor affecting the load transfer of the pile, which will alleviate the stress difference of rigid piles at different parts in the rigid-flexible pile composite foundation[4], reduces the stress concentration of the rigid pile, which is beneficial to flexible pile and soil parameter and bearing capacity. A lot of discussions have been done on the problem of load transfer law of piles. To sum up, the reasons affect the load transfer law of the pile are not only the properties of the pile tip soil characteristic mentioned in the paper, the rigidity and the length diameter ratio of the pile, the cement mixing ratio, the soil type, the moisture content, the compactness, the use of the cushion layer, etc., but also the following factors combined with the relevant data

1. Influence of stiffness ratio between pile tip soil and pile side soil (E_b / E_S).
   (1) E_b / E_S → 0, The soil quality of the pile tip is very poor, and the load is almost borne by the side friction, which belongs to the friction pile. For the uniform soil layer, the side resistance is nearly evenly distributed along the pile.
   (2) E_b / E_S → 1, The pile tip is the same as the pile side soil, which belongs to the friction pile of uniform soil, and the distribution of side resistance is similar to that of the previous one.
   (3) E_b / E_S → ∞, The soil on the pile side is very poor, while the pile tip is good. For the medium piles (L / D = 25), the lateral resistance of the upper section of the pile can be fully exerted. Because the relative displacement of the soil is small, the lateral resistance cannot be fully exerted. This type is end bearing pile.

2. Influence of stiffness ratio between pile and soil (E_p / E_S).
   (1) If the ratio of E_p / E_S is a large value. The greater rigidity of the pile, the larger proportion of the end resistance.
   (2) If the ratio of E_p / E_S is a small value. The lower stiffness of the pile, the smaller proportion of the end resistance.
   (3) For the medium piles (L / D = 25), E_p / E_S ≤ 10, The end resistance is close to zero. For example, gravel pile, sand pile, lime soil pile and cement soil pile, which are used to improve the strength of foundation soil, have low strength, its load transfer will not be affected. Therefore, the pile with a large length-diameter ratio is a friction pile, regardless of the soil properties of the pile tip. Under the condition that the settlement of pile tip remains unchanged, the load on pile tip increases with the increase of length-diameter ratio, while the load transfer rate decreases. When the ratio of pile length to diameter is not less than 40, the load ratio of pile tip resistance is close to zero in uniform soil layer.
3. Load transfer law

The load transfer law of the soft soil foundation of the expressway is analyzed from the mechanism of the combined treatment method[5]. Within a certain depth of the ground, the composite foundation composed of the cement soil mixing pile and the soil between the piles is not only used to improve the bearing capacity of the composite layer but also force the composite modulus of the foundation, in addition, reduce the total settlement of the foundation. Whether the interface between pile and soil is clear or not, there is negative friction between pile and soil within a certain range of the upper part of the pile, and the maximum stress section shall not be at the pile top[6]. Furthermore, it is found that short piles can weaken the negative friction effect and play the role of soil between piles better.

Through the experiments, the transfer rule of axial force of compacted cement soil pile and the distribution characteristics of side friction of pile are obtained as follows[7]:

(1) The failure of each pile shows obvious steep drop type. When the load is small, the deformation is small. When the load reaches a certain value, the deformation increases sharply, and there is a steep drop section, which indicates that the strength of the pile has reached its ultimate strength and is destroyed. Due to the limitation of the material strength, the increase of pile length can not significantly improve the ultimate bearing capacity of pile. The bearing capacity of pile can be improved obviously by increasing the proportion of materials.

(2) The axial force of the pile gradually decreases along the depth, and the attenuation is faster within about 10 times of diameter of the upper part of the pile (0-1.5m), and the lower variation gradient decreases. The compacted cement soil pile belongs to friction pile.

(3) The lateral friction of the pile increases rapidly in the range of 10 times of diameters (0-1.5m). When the load is close to the limiting value, the lateral friction on the upper part of the pile is fully exerted, while the friction on the lower part is less. The premature failure of the pile limits the exertion of the lateral friction on the lower part of the pile.

Zhang Shi-hua and Ma An-gang had tested the axial force of a pile in a substation in Lanzhou. They found that the exertion of pile shaft resistance depends on the stress-strain characteristics of the soil around the pile and the relative displacement of pile-soil. By analyzing the compressive and pull-out static loads of the bored pile in the loess site, especially in the very wet to saturated loess, this paper discussed the variation law of pile axial force and pile lateral friction resistance of the bored pile in the wet loess, and its load transfer law is mainly as follows:

(1) When the load at the top of the pile is small, the load is balanced with the friction of the pile, and the bottom is unstressed. With the increasing load on the top of the pile, part of the load is transferred to the bottom and increases gradually.

(2) In terms of the average friction between two sections, As the load increased average friction increasing,. When the pile top load approaches or reaches the ultimate load, The average frictional resistance between the two sections basically keeps a certain value and does not change significantly, indicating that the frictional resistance of this section has been fully exerted, and the increased load on the upper part will be transmitted to the lower part of this section.

(3) When the pulling force on the top of the pile is small, it is balanced with the friction resistance of the upper pile. With the increasing lead, the frictional resistance of the pile gradually extends downward.

(4) The law of load transfer of pile under vertical pressure: The force initially applied on the top of the pile is balanced with the frictional resistance; With the increase of the load, a large displacement occurs between the pile and the soil, and the side friction of the pile increases, furthermore, part of the force is transmitted to the bottom of the pile; keep loading, not only the friction resistance gradually reaching the extreme value along the pile from top to bottom, but also the load at the bottom gradually increasing to the extreme value, so that the bearing capacity of the foundation pile reaches the limit.

For rigid-flexible pile composite foundation[8]:

(1) In the composite foundation of rigid-flexible pile, both the rigid pile and the flexible pile have effective pile length, and the load transfer length of the rigid pile is larger than that of the flexible pile.
(2) Both the rigid pile and the flexible pile in the middle of the rigid-flexible pile composite foundation without a cushion have a small negative friction resistance when the load is small, after the load of upper structure increases, the negative friction is transformed into positive friction. The negative friction of rigid pile and flexible pile with cushion layer runs through the whole construction process, but the mechanism of negative friction is different.

(3) The friction resistance of the lower part of the central rigid pile is greater than that of the side rigid pile, while the opposite situation appears in the upper part, the center of gravity of the friction resistance of the middle rigid pile is lower than that of the edge rigid pile.

(4) The end bearing capacity of middle rigid pile and flexible pile is higher than that of edge rigid pile and flexible pile.

4. Optimization methods for influencing factors

For the soft soil foundation treatment of expressway, the most common and mature methods are drainage consolidation method and cement-soil mixing pile. Drainage consolidation method is to install vertical drainage bodies such as sand wells (bagged sand wells or plastic drainage belts) in natural foundations, and then gradually load by the weight of the building itself; Or the method of loading preload on the site before the construction of the building, so that the pore water in the soil is discharged and gradually consolidated, moreover, the foundation is settled, and the strength is gradually increased. Cement soil mixing pile is a method used to strengthen saturated soft clay foundation. It uses cement as the curing agent, through a special mixing machine, the soft soil and the curing agent are forced to mix in the depth of the foundation, and a series of physical and chemical reactions between the two material are made the soft soil turned into a high-quality foundation with integrity, water stability and certain strength. It is found that, for deep soft soil foundation, the consequence is not ideal if the drainage consolidation method or cement soil mixing method are used alone. It is an effective treatment method to consolidate deep soft foundation with cement soil mixing pile and plastic drainage board[9-10]. The study found that the combined treatment of the two methods is conducive to drainage consolidation of the lower soft soil. The analysis also believes that because the cement-soil mixing pile treats the upper soft soil to form a composite foundation, the bearing capacity and stability of the foundation are improved, so that the rate of soil filling can be accelerated, and the construction period is shortened.

Rammed cement-soil pile composite foundation is also a new technology for foundation treatment[9]. The rammed cement-soil pile is used to form holes by hand or machinery. It uses relatively single soil and mixes with cement in a certain ratio. It is fully mixed evenly outside the hole to produce cement-soil, backfilled layer by layer to the hole and rammed strongly to make the cement-soil pile uniform. Finally the pile, the soil between the piles and the cushion layer constitute a composite foundation together. As a medium bond strength pile, rammed cement soil pile is not only suitable for the foundation reinforcement of muddy soil, plain fill, silt and silty clay above the groundwater level, but also an effective method for the foundation reinforcement under the groundwater level after the dewatering treatment. The rammed cement-soil pile improves the strength of the foundation through two aspects: one is to compact the soil between piles in the process of pile compaction, so that the strength of soil around piles can be improved to a certain extent; the other is to ram cement and soil into piles, and a series of physical and chemical reactions such as ion exchange can be produced after cement and soil are mixed, so that the pile could obtain strength and hydraulic. After treatment, the strength and deformation resistance of the composite foundation were significantly improved. The main difference from the mixing cement soil pile is that the cement soil of the rammed pile is fully mixed and compacted, and its uniformity and compactness are much higher than that of the mixing cement soil pile, and the strength of the rammed pile is 2-10 times of the mixing cement soil pile. For the method of measuring the axial force of the cement-soil pile, Yang Guang-qing and others used different methods[12-14] to test the pile load of the cement-soil pile. For the rammed cement-soil pile composite foundation[15], the factors affecting load transfer mainly include the strength of the material, the pile length, and the cement mixing ratio. The effect of
increasing cement mixing ratio to improve load transfer depth of rammed cement – soil pile is not obvious. Under the condition of reference[2], the distribution characteristics of pile side friction resistance do not show any significant difference when the cement mixing ratio is normal usage.

5. Conclusion
Using inductive analysis method to carry out a systematic and deep study on the load transfer law of the pile foundation, the following results have been obtained:

1. Based on the analysis of the mechanical characteristics of the pile, the main factors influencing the load transfer of the pile are discussed, and the relevant engineering control indexes are put forward.
2. Pile bearing capacity and the amount of cement varies linearly.
3. With the increase of the deformation modulus of the soil at the pile end, the settlement of the pile foundation decreases under different loads.
4. The factors affecting load transfer mainly include the strength of the material, the pile length, and the cement mixing ratio. The effect of increasing cement mixing ratio to improve load transfer depth of rammed cement – soil pile is not obvious.

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