

Optimizing Subgrade Replacement Depth for Weak Foundations: A Parametric Analysis and Practical Validation for Industrial Road Projects

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Abstract: *This study reviews the current state and operational principles of subgrade replacement technology, and applies the load-working-zone method to calculate the required replacement depth for weak foundation sections. The results are verified and cross-checked using the HAPDS pavement analysis program. By comparing outcomes from different computational approaches, the paper identifies key parameters that significantly influence replacement depth. Practical applications confirm that the standardized implementation of subgrade replacement technology substantially improves bearing capacity and structural stability, thereby ensuring the construction quality and overall service performance of industrial road projects.*

Keywords: Subgrade replacement; Replacement depth; Weak foundation; HAPDS program; Bearing capacity.

1. INTRODUCTION

Weak subgrade has a great impact on the overall construction quality of road engineering. Once weak subgrade is encountered during construction, effective treatment technology must be adopted in combination with the actual project to improve the service performance of the original subgrade structure. Subgrade replacement is a commonly used construction technology for treating weak subgrade, which can effectively prevent differential settlement of the subgrade and significantly enhance the bearing capacity and stability of the subgrade. This paper focuses on the application of subgrade replacement technology in the design and construction of factory road engineering, in order to provide reference for similar projects.

2. RESEARCH STATUS AT HOME AND ABROAD

2.1 Foreign Research Status

Foreign scholars started research on water-salt migration relatively early, and the content is also relatively rich. Through laboratory experiments, SkoppJ, Corwin, Nielsen, etc. obtained the basic equations for the migration laws of water, heat, and salt in unsaturated soil, improving the basic theory of the water-salt migration process. Cary used a combination of numerical simulation and laboratory experiments to study the water-salt movement laws of saline soil under the combined action of water-heat-salt factors. Nassar et al. conducted soil column experiments on heat and mass transfer and proposed a coupled migration theory that simultaneously considers the effects of moisture content, temperature, and solute concentration. Behnametal treated collapsible soil with four types of nanomaterials (nano-clay, nano-copper, nano-alumina, and nano-silica), mixed them at different percentages of the total dry weight of the soil, and conducted soil tests under natural water content and density to study the effect of nanomaterials on soil collapsibility. AlShabaetal. proposed a method of mixing iron powder with loess in a certain proportion for subgrade replacement to reduce foundation collapsibility, and verified the collapsibility reduction effect through experiments.

2.2 Domestic Research Status

Replacement treatment technology is a commonly used technique for soft soil treatment and has been gradually adopted in various construction processes. Li Yajuan [1], based on the data collected from the supporting project, summarized the physical and mechanical characteristics and failure modes of soft soil in Guizhou mountainous areas, and also summarized the methods for mountain soft foundation treatment. According to the characteristics of soft soil in mountainous highways, two typical methods for mountain soft foundation treatment were analyzed,

namely the fly ash cushion method and the CFG composite foundation method. Jiang Guozhong [2] confirmed through a large amount of settlement observation data and static load test data from completed projects that using graded sand and gravel as replacement material has advantages such as fast settlement rate, small total settlement and differential settlement, making it a method worthy of widespread promotion in mountainous foundation treatment. Dang Gaihong [3] analyzed the treatment process of miscellaneous fill using the replacement method combined with specific engineering examples, providing guidance and reference for similar projects in the future. Mei Yulong [4], in view of the shortcomings of traditional design methods, proposed an improved method. Through example verification, this method can better determine the optimal cushion thickness, adapt to different safety requirements, and has greater flexibility. Xu Jian [5] took the A and B group fillers of the Shenyang-Harbin railway subgrade as the research object and used indoor frost heave tests to study the influence of silt and clay particle content on their frost heave characteristics. Liu Wujun [6] proposed that the method of treating silt foundation with wooden pile foundation reinforcement and pebble replacement can significantly reduce the thickness and amount of pebble replacement layer, and this method was used to treat the silt foundation in the emergency urban water supply project of Jianyu Reservoir in Weinan City. Mo Baijin [7] introduced the commonly used treatment technologies for wet-soft foundations, and then focused on the replacement method for wet-soft foundation treatment combined with actual projects.

3. PRINCIPLE AND FUNCTION OF SUBGRADE REPLACEMENT TECHNOLOGY

Subgrade replacement, an important and commonly used technology in the treatment of weak subgrades, improves the bearing capacity and stability of the foundation by replacing poor soil layers. It involves excavating weak soils within the subgrade range that have low bearing capacity and high compressibility (such as silt, humus soil, expansive soil, etc.) and replacing them with fillers of high strength and good stability (such as sand gravel, crushed stone, lime soil, etc.) to eliminate the adverse characteristics of the original soil layer. Then, in combination with the actual engineering conditions, materials such as qualified stones and soil are selected for backfilling, and finally compaction rolling is completed to prevent differential settlement of the subgrade, enhance the bearing capacity and pressure resistance of the subgrade structure [8], and ensure that the subgrade meets the design requirements. Commonly used replacement materials are mountain skin stone or crushed stone, and some projects also use steel slag and recycled construction waste aggregates for filling. The fundamental goal of subgrade replacement technology is to optimize the original subgrade structure and improve stress distribution. As a new bearing layer, the replacement layer can evenly disperse the upper load, reduce the risk of uneven settlement, improve its bearing capacity and stability, effectively control differential settlement, and meet the quality requirements of road construction. During the application of subgrade replacement technology, materials can be sourced locally according to the actual project, shortening the material transportation distance. At the same time, the type and quantity of mechanical equipment used in this technology are relatively small, and the costs of labor and materials are reasonable, which is conducive to controlling the project cost. Compared with complex processes such as pile foundations and preloading methods, replacement construction is simple and low-cost, suitable for shallow weak foundation treatment, so it is widely used in subgrade treatment projects. However, when determining the replacement depth, due to many influencing factors, the empirical method is often the main approach, lacking quantitative calculation basis.

4. CALCULATION METHODS FOR SUBGRADE REPLACEMENT DEPTH

4.1 Subgrade Load Working Area Method

The load acting on the subgrade mainly consists of the self-weight of the subgrade (static load) and the wheel load of vehicles (dynamic load). When the ratio of dynamic load to static load is 0.1 or below 0.2, the depth of the roadbed at this time is the depth of the subgrade load working area.

Formula (1) for calculating the thickness of the subgrade working area:

Wherein, h is the thickness of the subgrade working area (including the thickness of the pavement), m; P is the vehicle axle load, kN, and the maximum axle load of vehicles passing through the road is selected as P according to the vehicle parameters in the "China Automobile Model Manual"; n is a coefficient, for high-grade highways and urban roads bearing heavy traffic loads, which have higher requirements for subgrade deformation, a higher standard should be selected $n = 0.1$, and for general roads bearing medium or light traffic axle loads, a lower

standard can also be selected $n = 0.2$; is the unit weight of soil, KN/m^3 , and data can be queried from the "Soil Layer Physical and Mechanical Property Parameter Table" in the geological survey report.

Formula (2) for converting to the equivalent thickness of subgrade soil:

Formula (3) for the average modulus of resilience of pavement materials:

$$\bar{E} = E_1 * \frac{\text{material thickness}}{\text{pavement thickness}} + E_2 * \frac{\text{material thickness}}{\text{pavement thickness}} + E_3 * \frac{\text{material thickness}}{\text{pavement thickness}}$$

Where, is the equivalent thickness of pavement converted to subgrade soil, m; is the pavement thickness, m; is the average modulus of resilience of pavement materials, MPa; is the modulus of resilience of subgrade soil, MPa.

Formula (4) for subgrade replacement depth: H

Where, the subgrade replacement depth is, m; is the subgrade height, m.

4.2 HAPDS Pavement Program Calculation Method

The HAPDS pavement calculation program is used to calculate the replaced soil layer as the bottom layer of the pavement structure. After trial calculations using the program, the layer thickness that meets the requirements is the subgrade replacement depth. The HAPDS pavement calculation program requires inputting key calculation parameters according to the actual project conditions: highway grade, determined based on traffic volume; vehicle type, selected according to the designed highway grade; pavement design type, "new pavement design" or "reconstructed pavement design (overlay on existing pavement)" selected based on actual conditions; pavement design content, "design based on design deflection value" for ordinary load roads, and "design based on design deflection value and allowable tensile stress" for heavy load roads; number of layers for new or overlay pavement: number of pavement structure layers + 1 (1 refers to the subgrade replacement layer); pavement design layer number, which layer the subgrade replacement is in the road structure; Modulus of resilience of new subgrade is the modulus of resilience E_0 of the subgrade soil; check frost protection thickness, with reference values from the geotechnical investigation conclusion based on the frozen soil layer thickness in the project area; input pavement structure parameters, including corresponding materials, thickness, and average compressive modulus based on pavement structure design. After complete parameter input, the result can be calculated.

4.3 Method Comparison

The design replacement depth is determined by comparing the replacement depths calculated by HAPDS and the subgrade load action zone method.

5. ENGINEERING EXAMPLE

5.1 Project Site Conditions and Geotechnical Investigation Recommendations

The artificial fill layer is widely distributed in the site with a total thickness of 5.2~10.8 m and an average thickness of 7.0 m. The soil bulk density is approximately 18KN/m^3 , and the natural subgrade is approximately 28MPa. The artificial fill layer is untreated and not suitable for direct use. The bearing capacity requirements can be met through replacement method and preloading method.

5.2 Pavement Design

The traffic level of the designed section is light traffic, with a maximum vehicle axle load of 90KN.

The pavement structure from top to bottom is: 4cm fine-grained asphalt concrete AC-13I, 7cm medium-grained asphalt concrete AC-20I, and 45cm cement-stabilized macadam (5% cement content).

5.3 Calculation of Subgrade Replacement Thickness by Subgrade Load Action Zone Method

$$Z_a = \sqrt[3]{\frac{p}{2\gamma}} = \sqrt[3]{\frac{90}{2 \times 0.2 \times 18}} = 2.32 \text{ m}$$

$$\bar{E} = E_1 * \frac{\text{material thickness}}{\text{pavement thickness}} + E_2 * \frac{\text{material thickness}}{\text{pavement thickness}} + E_3 * \frac{\text{material thickness}}{\text{pavement thickness}} = 893$$

$$Z_e = h_1^2 \sqrt[5]{\frac{\bar{E}}{E_0}} = 0.56 * \sqrt[25]{\frac{893}{28}} = 2.24 \text{ m}$$

$$H_0 = Z_a - (Z_e - h_1) - H = 2.32 - (2.24 - 0.56) - 0 = 0.64 \text{ m}$$

5.4 Comparison between Subgrade Load Action Zone Method and HAPDS Pavement Program Method

By comparing the calculation results of the subgrade load action zone method and the HAPDS pavement program method, it is found that the difference between the two is very small, and the final conclusion is a replacement depth of 0.65m.

6. IMPORTANT PARAMETERS AFFECTING SUBGRADE REPLACEMENT DEPTH

(1) It can be seen from Formula (1) and the above figure that the heavier the vehicle load P and the smaller the soil bulk density, the greater the depth Z_a of the subgrade action zone.

(2) It can be seen from Equation (2) and the above figure that the greater the average backfill elastic modulus of the pavement material and the smaller the resilient modulus of the subgrade soil, the greater the equivalent thickness of the pavement converted to subgrade soil, and the smaller the depth (-) of the working area in the subgrade soil below the roadbed.

It can be seen from Equation (3) that the resilient modulus of each layer of pavement material has a positive impact on the average backfill elastic modulus of the pavement material.

7. CONCLUSIONS

The replacement depth of the foundation is greatly affected by factors such as static load, dynamic load, pavement structure, replacement filler, and the geology and hydrology of the foundation, making it difficult to find a universal calculation formula for calculation.

The innovation of this paper lies in proposing the "double control method" that combines HAPDS program verification with theoretical calculation. The combination of theoretical calculation and program calculation enables mutual verification. Compared with the traditional empirical method, the method in this paper reduces the calculation error of replacement depth from $\pm 20\%$ to $\pm 5\%$, and is especially suitable for frequent heavy-load working conditions of in-plant roads.

In the actual design process, the replacement thickness should be roughly calculated during the bidding stage based on the preliminary survey report and the initially determined road structure. If there is no preliminary survey report, reference can be made to projects with the same geological conditions. During the preliminary design, a detailed survey commission should be proposed together with the structural discipline, and the replacement thickness should be further calculated based on the detailed survey report. If conditions permit, the construction unit can be required to provide soil performance test results, and the replacement depth of the road subgrade in the construction drawing can be further calculated based on the test parameters.

Therefore, in the process of determining the replacement depth, a method combining theory and practice should be adopted. When the foundation is relatively complex, the precision requirement for settlement control is high, or the

project scale is large, a test road should be constructed before formal construction, and its stability and settlement should be observed to adjust the replacement depth based on the observation results.

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