Highway Subgrade Workaround: Surveys, Assessments and Practical Implications

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Abstract: The definition and determination method of the highway subgrade workaround remain insufficiently clear and explicit. Therefore, this paper summarizes the current mainstream determination methods, and analyses and compares their characteristics, advantages, and disadvantages. Based on the method specified in the current highway subgrade design specification, and combined with the elastic layered system theory computer program GAMES, the distribution of vertical additional stress, self-weight stress, and stress ratio along the axle-direction profile under loading is presented. The WorkAround program is introduced to discuss the influence laws of multiple factors on the subgrade workaround. It is concluded that pavement modulus, pavement unit weight, subgrade unit weight, and pavement thickness are negatively correlated with the subgrade workaround, while subgrade modulus and axle load are positively correlated with the subgrade workaround. Combined with orthogonal experimental design, the influence degrees of these factors on the subgrade workaround are revealed, leading to the conclusion that the order of influence is: pavement thickness > axle load > subgrade modulus > pavement modulus > subgrade unit weight > pavement unit weight.

Keywords: Subgrade workaround, Elastic layered system theory, Stress ratio, GAMES program, WorkAround program.

1. INTRODUCTION

As a strip-shaped structure constructed in accordance with route alignment and certain technical requirements, the subgrade is the foundation of the pavement structure and bears the traffic loads transmitted through the pavement. Obviously, the traffic loads are transferred and diffused through the pavement, and the vertical additional stress within the subgrade gradually attenuates from top to bottom. On the other hand, the closer to the bottom surface of the pavement, the greater the influence of external water and temperature on the subgrade. To accommodate these requirements, the important concept of "subgrade workaround" has been introduced into the highway industry. This concept holds that there exists a depth range within the subgrade that bears non-negligible vertical additional stress induced by traffic loads. When this depth range is measured from the top of the subgrade, it is referred to as the "subgrade workaround"; when measured from the pavement surface, it is commonly termed the "subgrade workaround depth". Within this range, superior embankment fill materials and more stringent compaction requirements are naturally required, whereas beyond this range, such requirements may be appropriately relaxed, thereby achieving a sound balance between engineering technicality and economic efficiency.

The introduction of the concept of subgrade workaround is undoubtedly of strong engineering significance. In the determination of roadbed thickness, the *Specifications for Design of Highway Subgrades* (JTG D30—2015) states that the roadbed range is determined based on subgrade workaround depth [1]. For highways with special axle loads, the subgrade workaround should be calculated separately to determine the roadbed thickness. In the design of asphalt pavements, the subgrade moisture condition needs to be determined according to the relative positions of the subgrade workaround, the capillary wetting surface, and the groundwater table. Based on this, the design value of subgrade resilient modulus can be determined.

However, despite the considerable importance of the subgrade workaround concept, there still exist some prominent problems in current research on this subject. On the one hand, many researchers have attempted to propose corresponding determination methods from perspectives such as stress ratio and strain ratio, but regrettably, there has been no public report that systematically summarizes, reviews, and compares these determination methods to date. On the

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other hand, the factors affecting the subgrade workaround are diverse, covering traffic loads, pavement, subgrade, etc. Some researchers have discussed the influence trends of these factors on the subgrade workaround, but the factors considered are still incomplete and unsystematic [2, 3]. In addition, the ranking of the influence weights of these factors on the subgrade workaround remains unclear.

Based on this, the present paper attempts to summarize the current determination methods for the subgrade workaround, compare and analyze their respective characteristics, advantages, and disadvantages. With the aid of the elastic layered system theory-based computer program GAMES, this paper illustrates the distributions of vertical additional stress and self-weight stress along the cross-section along the axle direction under loading. The WorkAround program is introduced to discuss the influence trends of multiple factors on the subgrade workaround. In combination with orthogonal experimental design, the degrees of influence of these factors on the subgrade workaround are revealed.

2. SUMMARY AND CRITICAL REVIEW OF EXISTING DEFINITIONS OF SUBGRADE WORKAROUND

2.1. Summary of Existing Definitions and Calculation Methods

A brief summary of the current definitions and determination methods for the subgrade workaround in the industry is provided below.

2.1.1. Ratio of Vertical Additional Stress to Self-Weight Stress

The current *Specifications for Design of Highway Subgrades* (JTG D30—2015) defines the subgrade workaround as the depth range of stress distribution within which the ratio of the stress (transmitted from vehicle loads through the pavement to the subgrade) to the self-weight stress of the subgrade soil exceeds 0.1 [1]. The core issue lies in correctly solving for the vertical additional stress and the self-weight stress. For the calculation of vertical additional stress, either the semi-infinite elastic space model or the elastic layered system may be adopted.

If treated as a semi-infinite body, *Subgrade Engineering* [4], *Highway Design Manual: Subgrade* [5], and *Subgrade and Pavement Engineering* [6] assume that, under the condition of the subgrade being a semi-infinite body, the wheel load is a vertical concentrated load, and the vertical additional stress is calculated according to Equation (1).

$$\sigma_z = K\frac{P}{Z^2} \tag{1}$$

where *K* is a coefficient, $K = 3/(2\pi)$, generally taken as 0.5; *P* is the wheel load on one side (kN), taken as 50 kN for the standard axle load; and *Z* is the depth of the point of interest under the vertical concentrated load (m).

The self-weight stress σ_B of the subgrade soil induced at depth *Z* within the subgrade is calculated by Equation (2):

$$\sigma_B = \gamma Z \tag{2}$$

where γ is the unit weight of the soil (kN/m³).

For earth road, a simplified formula for calculating the subgrade workaround depth *Z* can be derived, as shown in Equation (3):

$$Z = \sqrt[3]{\frac{KnP}{\gamma}} \tag{3}$$

where *n* is a coefficient, *n*=10 (i.e., the reciprocal of the stress ratio limit of 0.1).

For conventional pavement structures, since the pavement-subgrade system is not a homogeneous body, and the stiffness and unit weight of the pavement are greater than those of the subgrade soil, the actual depth of the subgrade workaround decreases with increasing pavement stiffness and thickness. Therefore,

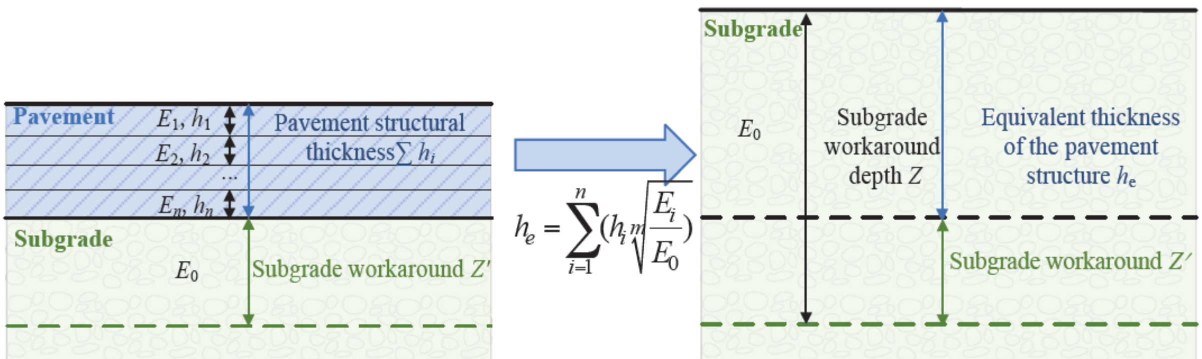


Figure 1: Conversion of the pavement-subgrade structure into a pure subgrade structure.

if the simplified stress Equation (1) is adopted, the asphalt pavement consisting of multiple structural layers needs to be converted into an equivalent homogeneous body with the same properties as the subgrade, as shown in Figure **1**, to obtain the equivalent thickness h_e of the asphalt pavement. In this case, the pavement-subgrade system is transformed into a pure subgrade system, and the subgrade workaround depth can be directly solved by Equation (3).

In Figure **1**, h_i is the thickness of each structural layer of the asphalt pavement (cm), *i* = 1, 2, …, *n*; E_i is the elastic modulus of each structural layer of the asphalt pavement (MPa), *i* = 1, 2, …, *n*; and E_0 is the resilient modulus at the subgrade top (MPa). The exponent *m* is taken as 0.35 in *Subgrade and Pavement Engineering* [6], and as 0.25 in *Subgrade Engineering* [4] and *Highway Design Manual: Subgrade* [5].

The subgrade workaround Z' is then obtained by subtracting the equivalent thickness h_e of the pavement structure from the subgrade workaround depth *Z*, as given in Equation (4).

$$Z' = Z - h_e \tag{4}$$

If treated as a layered elastic system, under a circular uniformly distributed load, the vertical additional stress can be directly calculated using computer programs developed based on the elastic layered system theory (such as BISAR, ELSYM5, and KENLAYER). The self-weight stress at the corresponding point depths can be obtained by layer-wise accumulation, and the ratio of vertical additional stress to self-weight stress can then be determined. By iteratively adjusting the depth to compute this ratio, the subgrade workaround can be obtained.

2.1.2. Ratio of Vertical Additional Strain to Self-Weight Strain

Zhou *et al*. noted that most of the existing methods for predicting permanent deformation of highway subgrades are strain-based regression models [7]. Therefore, for consistency, they proposed using the ratio of the additional strain ε_z induced by axle load to the self-weight strain ε_c of the pavement structure and subgrade soil, with a threshold of 0.1, as the criterion for determining the subgrade workaround depth, as shown in Equation (5). Both the additional strain and the self-weight strain are obtained using finite element programs.

$$\frac{\varepsilon_z}{\varepsilon_c} = 0.1 \tag{5}$$

2.1.3. Ratio of Additional Dynamic Stress to Self-Weight Stress

Lu *et al*. argued that it is necessary to employ dynamic methods to investigate the influence depth of traffic loads, and proposed an exact stiffness matrix method for calculating the vertical additional dynamic stress under dynamic loading [8]. To reduce the matrix dimension and facilitate the solution, the multilayer system is first converted into a three-layer system using the Odemark equivalent conversion formulas for thickness and resilient modulus, as shown in Equation (6), and then the vertical additional dynamic stress is calculated using the exact stiffness matrix method. The subgrade workaround depth *Z* is obtained by setting the ratio of additional dynamic stress to self-weight stress to 0.1.

By performing extensive calculations under various conditions considering the equivalent pavement thickness, subgrade modulus, and traffic axle load, a quantitative expression for the subgrade workaround depth was finally summarized, as shown in Equation (7).

$$h_e = (\frac{E}{E_1})^{1/3} h_0 \tag{6}$$

$$Z = Z_{100} + k(P - 100) \tag{7}$$

where h_e is the equivalent thickness after conversion (m); *E* is the resilient modulus before conversion (MPa); h_0 is the thickness before conversion (m); E_1 is the reference resilient modulus of the underlying layer (MPa). *Z* is the subgrade workaround depth (m); *P* is the axle load (kN); Z_{100} is the subgrade workaround depth under the standard axle load of 100 kN; and *k* is a fitting parameter, the value of which depends on the subgrade modulus and the equivalent pavement thickness.

Song *et al*. proposed a comprehensive method for determining the subgrade workaround of semi-rigid pavements based on the influence of vehicle dynamic loading [9]. First, the load form shown in Equation (8) is used to investigate the dynamic response characteristics of the subgrade:

$$P(t) = P_0 + P\sin(\omega t) \tag{8}$$

where P_0 is the vehicle static load, taken as the single-side wheel load of the vehicle (kN); *P* is the amplitude of the vibration load, $P=M_0\mu\omega$ (kN); M_0 is the sprung mass of the vehicle model (kg); ω is the circular frequency of vibration, $\omega=2\pi v/L$(s^{-1}); *v* is the vehicle speed (m/s); *L* is the wavelength of the pavement geometric profile (m); and μ is the amplitude of the pavement geometric irregularity (mm), the value of which is taken in accordance with the International Roughness Index for expressways.

Then, the Abaqus finite element software is used to simulate the pavement model and apply dynamic loads at different speeds. The dynamic stress values at various depths under dynamic loading are extracted and the ratio of dynamic stress to self-weight stress is calculated. The depth at which σ_Z / σ_B =1/10 is then determined as the subgrade workaround depth.

2.1.4. Ratio of Additional Maximum Principal Stress to Self-Weight Stress

Yan *et al*. proposed that the subgrade depth at which the maximum principal stress σ_1 induced by vehicle loads reaches 0.1 to 0.2 times the self-weight stress σ_B should be taken as the subgrade workaround [10]. The travel path within the finite influence range of vehicle loads was discretized, and the edge point of the stress influence zone where the maximum principal stress is greatest and the point at the bottom of the wheel were selected as key points for subgrade stress calculation. The maximum principal stress generated by vehicle loads within the finite region was then calculated. Based on the ratio of the maximum principal stress σ_1 induced by vehicle loads to the self-weight stress σ_B, a general formula for calculating the subgrade workaround of asphalt pavements was derived, with the calculation process shown in Equations (9) through (12).

$$\sigma_1 = \frac{2F_{max}\beta\psi(x^3 + xy^2)}{\pi(x^2 + y^2)^2} \tag{9}$$

$$\psi = 1 + i \tag{10}$$

$$\sigma_B = \gamma_0 z_0 + \gamma_1 z_1 + \gamma_2 z_2 + \gamma_3 z_3 = \gamma_1(1 + \alpha_1 + \alpha_2 + \alpha_3)Z' \tag{11}$$

$$Z' = \frac{2F_{max}\beta\psi(x^3 + xy^2)}{\pi\gamma_0(1+k)(x^2 + y^2)^2} \tag{12}$$

where F_{max} is the maximum load of a single wheel (MPa); β is a coefficient, β =5~10; *x*, *y* are the plane coordinates; γ_0 is the unit weight of the subgrade soil (kN/m³); *k* is a coefficient, $k = \alpha_1 + \alpha_2 + \alpha_3$; $\alpha_1, \alpha_2, \alpha_3$ are the unit weight ratios of the asphalt surface layer, cushion layer, and base layer to the subgrade soil, respectively; and *i* is the impact additional coefficient, taken as 0 to 0.45.

2.1.5. Ratio of Vertical Additional Stress to Static Compressive Strength

Huang and Ling considered the subgrade workaround as the zone near the upper soil layers where the vertical additional stress is relatively large and excessive cumulative plastic deformation is prone to occur, and this zone controls the cumulative plastic deformation of the entire subgrade [11]. They pointed out that based on the fundamental purpose of controlling the cumulative plastic deformation of the subgrade induced by vehicle loads, the ratio of vertical additional stress to static compressive strength should be adopted as the basis for determining the subgrade workaround depth.

2.1.6. Ratio of vertical Additional Stress to Yield Strength

Zhao, based on shakedown theory, proposed that the subgrade workaround is the range of soil within the subgrade that undergoes plastic deformation [12]. Under static loading, there always exists a certain depth in the subgrade or foundation below which the subgrade soil remains in a fully elastic state (i.e., the zone where the vertical stress in the soil is less than the yield strength of the soil). The zone above this fully elastic region is defined as the subgrade workaround, as shown in Figure **2**.

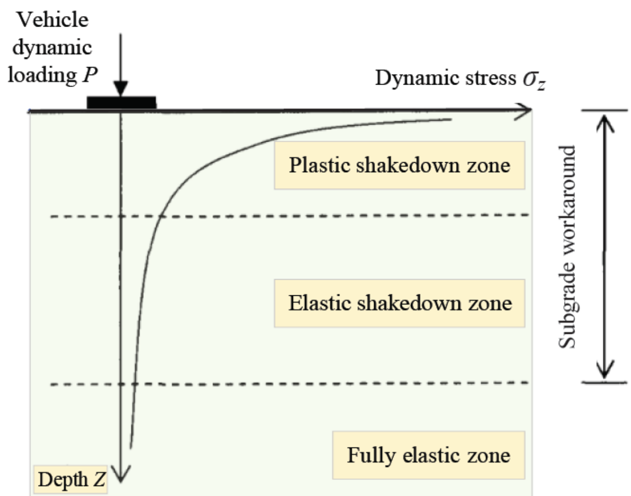


Figure 2: Subgrade workaround based on shakedown theory (modified from [12]).

Regarding the calculation of yield strength, Zhao conducted triaxial tests on silt and defined the maximum first principal stress in the linear segment of the stress-strain curve as the yield strength of the subgrade soil [12]. Through the relationship curve between yield strength and confining pressure, the formula for calculating the yield strength of silt was obtained, as shown in Equation (13), where the confining pressure is equal to the lateral self-weight stress in the soil, as given in Equations (14) and (15).

$$\sigma_s = 2.67\sigma_3 + 135 \tag{13}$$

$$\sigma_{ch} = K_0 \gamma z \tag{14}$$

$$\sigma_3 = \sigma_{ch} \tag{15}$$

where σ_s is the yield strength of the soil (kPa); σ_3 is the confining pressure (kPa); σ_{ch} is the lateral pressure of the soil at a certain point in the foundation (kPa); K_0 is the lateral pressure coefficient of the soil; γ is the unit weight of the soil (kN/m³); and *z* is the depth of the calculation point from the ground surface (m).

The vertical additional stress is calculated, and the depth at which the yield strength equals the vertical additional stress is taken as the subgrade workaround depth *Z*.

2.2. Comprehensive Review of Current Calculation Methods

From the summary of existing determination methods presented above, it can be seen that the highway industry is essentially attempting to introduce stress ratio, strain ratio, etc. to determine the subgrade workaround, though the numerator and denominator terms differ. A further analysis is provided below.

2.2.1. Comprehensive Review of the Numerator in Current Calculation methods

(1) If the vertical additional stress is taken as the numerator, it can be calculated in two ways: one is to use the relatively classical simplified analytical method for calculation, and the other is to use programs based on layered elastic theory or finite element programs for calculation.

Since the Boussinesq solution is derived from semi-infinite subgrade, when it is used for the calculation of pavement-subgrade structures, the pavement structure must first be converted into a subgrade structure through equivalent modulus conversion. This process neglects the differences in other material properties between the pavement and the subgrade, such as Poisson's ratio and unit weight, and also cannot take into account the superposition effects of different axle load types in subsequent calculations. Previous researchers, in the practical calculation of pavement-subgrade engineering, have found that in most cases the calculated subgrade workaround depth tends to be small. Moreover, it was found that the subgrade workaround depth calculated under pure subgrade conditions agrees well with the BISAR results, indicating that it should be the equivalent conversion formula that is inappropriate [11]. In the case of calculating multi-layered systems, it is still necessary to use computer programs based on layered elastic theory or finite element programs for calculation. This method is widely used, highly feasible, and well-recognized, and can effectively avoid performing the equivalent thickness conversion of the pavement.

However, it should be noted that when layered elastic system computer programs are used, the calculation points need to be manually input. Therefore, if an accurate subgrade workaround depth is to be obtained, adding calculation points is inevitably required. On the other hand, when finite element programs are used for calculation, they generally directly output the mechanical responses at elements and nodes, without the need to manually add calculation points. However, during the calculation process, they are inevitably affected by factors such as mesh, precision, and calculation model during modeling, and the sources of the errors affecting the results are difficult to identify.

(2) If the vertical additional strain is taken as the numerator, then the self-weight strain must be taken as the denominator. Although the determination of the subgrade workaround depth based on strain is consistent with the subsequent calculation of permanent deformation of the subgrade based on strain, the subgrade workaround depth obtained using the ratio of vertical additional strain to self-weight strain is greater than that obtained using the stress ratio, for reasons unknown [7].

(3) If the additional dynamic stress is taken as the numerator, the method for calculating this stress becomes a major issue. If the quantitative expression for the subgrade workaround depth is adopted directly from the literature, although this formula is simple, whether it contains errors, as well as the sources and magnitude of such errors, remain unknown to the user [8]. Moreover, it only focuses on three influencing factors, namely the equivalent pavement thickness, subgrade modulus, and traffic axle load, and extensive comparison with engineering practice is still needed to verify its reliability. On the other hand, if finite element programs are used to directly calculate the relevant dynamic stress by applying dynamic loads, the user is required to understand the mode of action of dynamic loads and the operation of finite element programs, which poses a high threshold and is not universally applicable [9].

(4) If the additional maximum principal stress is taken as the numerator, the calculation formula for the maximum principal stress derived in the literature appears not to take into account the material properties of the pavement-subgrade structure, and it is based on the maximum load of a single wheel, without considering the superposition effect of loads [10].

Table 1: Comprehensive Review of the Denominators in Current Calculation Methods

Denominator	Calculation method	Review
Self-weight stress	Layer-wise accumulation	It offers convenient and fast calculation, high feasibility, and wide acceptance.
Static compressive strength	Not specified	The method for determining the static compressive strength is not specified in the literature, nor has it been used for calculation based on this definition [11].
Yield strength	Empirical formula derived from triaxial tests	The yield strength formula derived in the literature is based solely on silt and does not possess universality for application to other soil types. Moreover, the errors for soils with different degrees of compaction cannot be ignored [12].
Self-weight strain	Finite element program	The self-weight strain can only be obtained using finite element programs, which introduces certain errors with unknown sources, and the application threshold is relatively high.

2.2.2. Comprehensive Review of the Denominator in Current Calculation Methods

A comprehensive review of the denominators in the current determination methods is presented in Table **1**. It is worth noting that the formula for self-weight stress derived in the literature appears to assume that the thickness of each layer of the pavement-subgrade structure is Z', which lacks universality [10].

3. FURTHER REFLECTIONS ON THE SUBGRADE WORKAROUND CONCEPT AS DEFINED IN THE *SPECIFICATIONS FOR DESIGN OF HIGHWAY SUBGRADES* (JTG D30-2015)

As mentioned above, many scholars have proposed different methods for determining the subgrade workaround, but the one that is most widely recognized and applied is still the method based on the ratio of the vertical additional stress induced by vehicle loads to the self-weight stress being greater than 0.1. This method has been incorporated into the *Specifications for Design of Highway Subgrades* [1]. However, previous studies have all been based on a certain point on the pavement surface, discussing the ratio of vertical additional stress to self-weight stress at different depths below that point [13-15], and there is still a lack of in-depth understanding of the distribution of the subgrade workaround along the axle direction. Therefore, this section, based on a specific numerical example and using the GAMES program based on elastic layered system theory, presents a thorough discussion for the intuitive determination of the subgrade workaround depth.

3.1. Description of the Numerical Example

The numerical example from Li is adopted for discussion [16]. The pavement structure comprises, from top to bottom, 4 cm of AC-13, 6 cm of AC-20, 7 cm of AC-25, 36 cm of cement-stabilized macadam, and 20 cm of lime-fly ash soil. with elastic moduli of 1500 MPa, 1250 MPa, 1000 MPa, 1500 MPa, and 200 MPa, respectively, and the subgrade resilient modulus is 36 MPa. The load is the standard axle load, with a

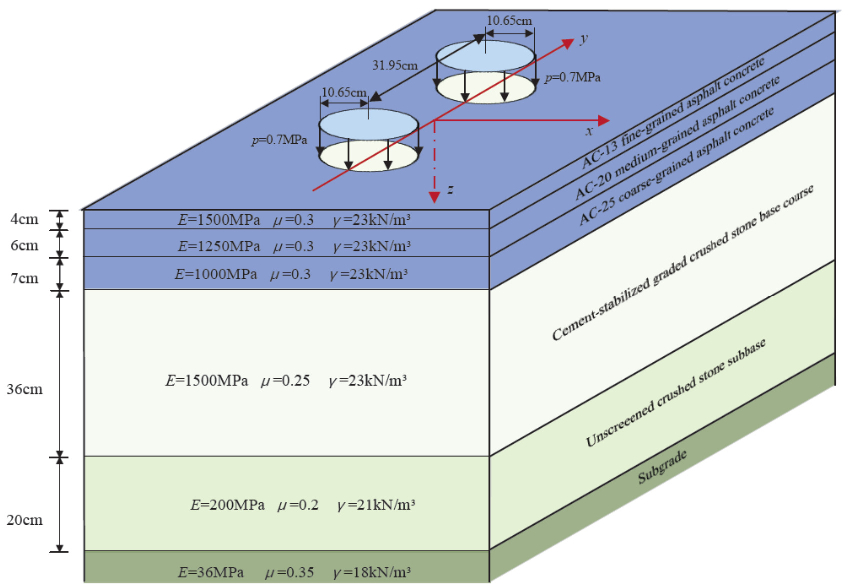


Figure 3: Pavement-subgrade structure and loading.

tire contact pressure of 0.7 MPa, a single-wheel contact equivalent circle radius of 10.65 cm, and a center-to-center spacing of the two wheels of 31.95 cm (i.e., 3 times the equivalent circle radius). See Figure **3** for details.

3.2. Model Establishment

The GAMES program, developed by Tokyo Denki University in Japan, is used to calculate the vertical additional stress. The program can accommodate up to 100 loads, 100 structural layers, and 10,000 calculation points, and can consider vertical loading and/or horizontal loading. In the calculation mode, it directly outputs the mechanical responses at each calculation point in Cartesian coordinates. It is particularly worth noting that, unlike other layered elastic computer programs, GAMES can also operate in a graphics mode, in which, without the need to input calculation point coordinates, it directly produces contour plots of vertical and longitudinal strains along any cross-section in the *x-y* and *x-z* planes, while also providing the mechanical responses at all points on the selected section.

Therefore, this paper adopts the graphics mode for calculation, as shown in Figure **4**. The following points should be noted during model establishment:

(1) When the GAMES graphics mode is selected, the program defaults the calculation thickness of the subgrade to the thickness of the second-to-last layer. If the original model is input as is, the calculation thickness of the subgrade would be 20 cm, and the total calculation depth would be 93 cm, which may be too shallow. Therefore, to ensure sufficient calculation depth, for this specific example, the semi-infinite subgrade is divided into two layers: 80 cm and the semi-infinite body, with the material parameters such as elastic modulus and Poisson's ratio being identical for both layers. By doing so, the calculation thickness of the subgrade in the graphics mode can be increased to 160 cm, with a total calculation depth of 233 cm, without affecting the calculation results.

(2) Regarding load parameters, when inputting the plane coordinates of the load circles, the GAMES program defaults the *x*-axis to the traffic direction. However, in the subsequent section selection, it cannot directly select a depth section along the *y*-axis (axle direction), and can only obtain a depth section along the *x*-axis (traffic direction). Therefore, in order to obtain the depth contour plot along the axle direction, the *x*- and *y*-axis coordinates need to be swapped when inputting the parameters. The traffic direction is set as the *y*-axis direction, and the centers of the two circles are positioned on the *x*-axis. The section in the *x-z* direction thus obtained is the desired section along the axle direction.

(3) After inputting the parameters of the example, select any one of the mechanical responses from the vertical and longitudinal strains, then choose the section in the *x-z* direction, enter 0 cm at the section location, and click on the analysis data. The contour plot of the distribution of the selected mechanical response along the section in the axle direction is then obtained, and a BRE file containing all the mechanical responses at all points on this section is generated in the corresponding folder.

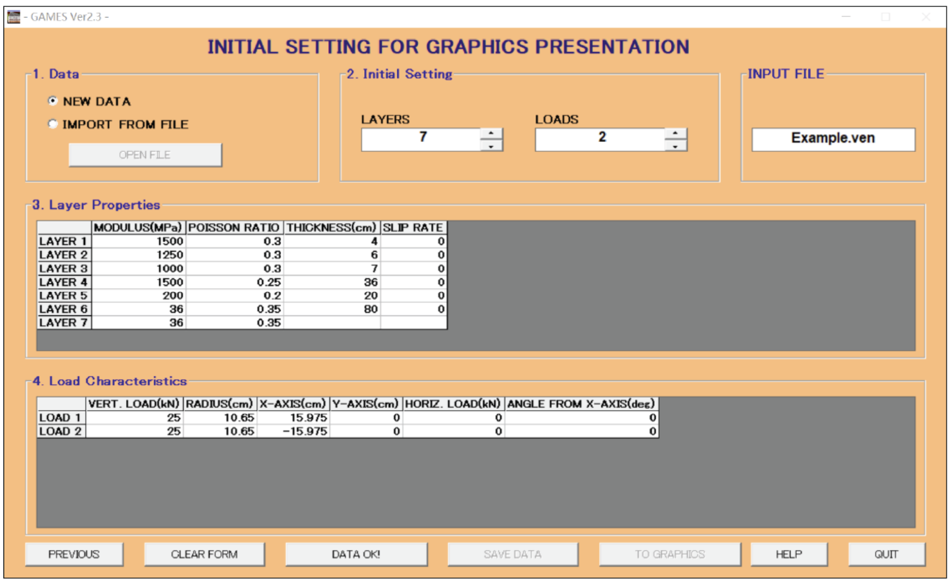


Figure 4: Setting the relevant parameters in the GAMES program.

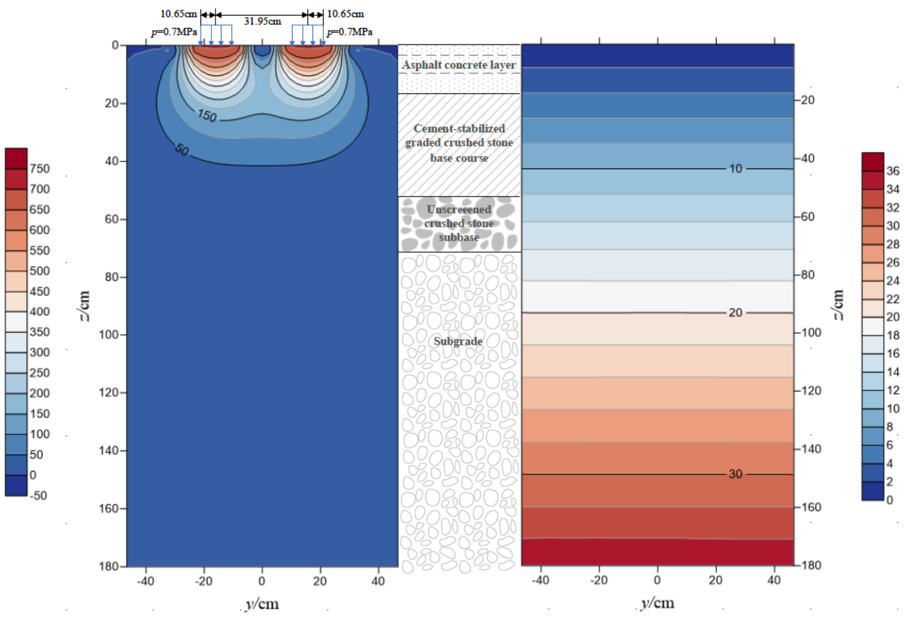


Figure 5: Distribution of vertical additional stress and self-weight stress in the pavement-subgrade system (unit: kPa).

3.3. Results Analysis and Discussion

The *x*- and *z*-coordinate columns and STRz (vertical additional stress) columns in the BRE file are extracted, and the corresponding self-weight stress can be quickly calculated using the *z*-coordinate of each point in combination with the unit weight of each layer. Obviously, by taking the ratio of the vertical additional stress to the self-weight stress at each point, the stress ratio at each point within the section along the axle direction can be obtained. However, a preliminary check indicates that the depth at which the stress ratio equals 0.1 is roughly in the range of 160 cm to 170 cm, which falls well within the previously adjusted calculation depth of 233 cm. For clarity and to highlight the key points, the visualization range is temporarily adjusted to 180 cm, as shown in the stress contour plot in Figure **5** and the stress ratio contour plot in Figure **6**. By observing Figure **6**, the extent of the subgrade workaround can be easily identified.

It can be seen from Figure **5** that under the action of dual circular uniformly distributed vertical loads, the vertical additional stress is relatively large near the surface, exhibiting a distinctly symmetrical double stress bubble pattern. With increasing depth, the vertical additional stress gradually decreases and transitions into a single stress bubble pattern. Under the self-weight of the pavement-subgrade system, the distribution of vertical self-weight stress maintains a horizontal layered pattern, and increases with depth. It can be seen from Figure **6** that the stress ratio decreases with increasing depth. Among the horizontal positions, the subgrade workaround depth below the center point of the wheel gap is the greatest. The contour lines exhibit a certain curvature rather than being purely horizontal, indicating that the calculated subgrade workaround depth varies with different horizontal positions. Observing the three contour lines corresponding to stress ratios of 0.1, 0.2, and 0.3, although the stress ratios are in arithmetic progression, the depth intervals between these three contour lines are different, indicating that although the stress ratio limits increase in arithmetic progression, the subgrade

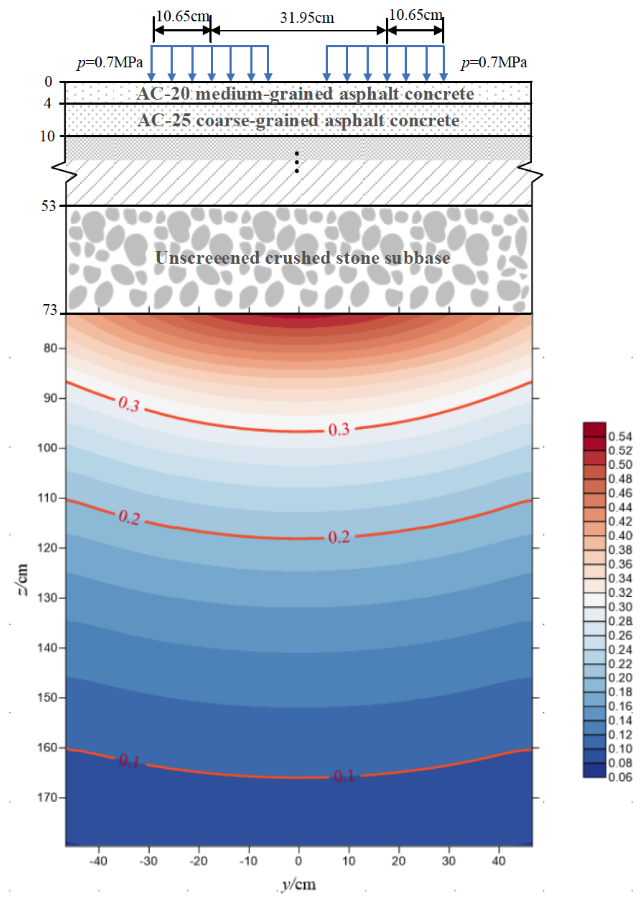


Figure 6: Ratio of vertical additional stress to self-weight stress in the subgrade.

workaround depth does not follow the same arithmetic progression.

4. DISCUSSION ON THE INFLUENCE TRENDS AND INFLUENCE DEGREES OF PARAMETERS RELATED TO THE SUBGRADE WORKAROUND

4.1. Influence Trends of Parameters Related to the Subgrade Workaround

From the perspective of conceptual design, it can be inferred that the subgrade workaround is comprehensively influenced by loads (such as tire contact pressure, single-wheel contact equivalent circle diameter, and center-to-center spacing of the two wheels) and structural layer parameters (such as layer thickness, unit weight, elastic modulus, Poisson's ratio, and interlayer bonding condition). For simplicity, this section idealizes the problem as a two-layer system, in which the surface course, base course, and subbase course are collectively represented as a single pavement structure. The load is set as a dual circular uniformly distributed load, with the load circle radius of δ, and the center-to-center spacing of the two wheels taken as 3δ, as shown in Figure **7**, to discuss the influence trends of the aforementioned parameters on the subgrade workaround.

The following considerations are taken into account: (1) Since the Poisson's ratio varies within a relatively narrow range, the Poisson's ratios of the subgrade and the asphalt pavement are fixed at 0.4 and 0.25, respectively, in the present analysis. (2) The interface bonding conditions between layers do not affect the distribution of vertical additional stress; therefore, no parametric analysis is conducted for this factor. (3) In practice, the load radius, load intensity, and center-to-center distance between dual wheels cannot be readily considered independently; hence, it is reasonable to treat these three parameters as a single influencing factor, namely, the axle load.

In summary, six influencing factors are selected in this paper, namely, pavement modulus, pavement unit weight, subgrade unit weight, pavement thickness, subgrade modulus, and axle load. Within the framework of determining the subgrade workaround by the ratio of vertical additional stress to self-weight stress, these six factors can, to a large extent, comprehensively cover the parameters required for the elastic layered system analysis of highway asphalt pavements, and can therefore adequately represent the actual conditions of highway asphalt pavements.

4.1.1. Introduction to the Calculation Program WorkAround and its Reliability Verification

Previous researchers have commonly used layered elastic theory programs such as BISAR to calculate the vertical stress. This approach requires successively increasing the calculation depth to obtain the vertical stress at each calculation point, and then calculating the stress ratio step by step until the ratio reaches 0.1, which is a somewhat lengthy and cumbersome process. For this reason, this paper introduces a program named "WorkAround" to directly calculate the subgrade workaround. This program can handle single-circle and dual-circle loads, and accommodates up to 20 structural layers (including the subgrade). It employs the bisection method to automatically calculate the ratio of vertical additional stress to self-weight stress at each depth point beneath the center of a single circle or beneath the center of the wheel gap of dual circles, and directly outputs the subgrade workaround (depth below the subgrade top) in the result file, with a calculation accuracy of 0.1 mm.

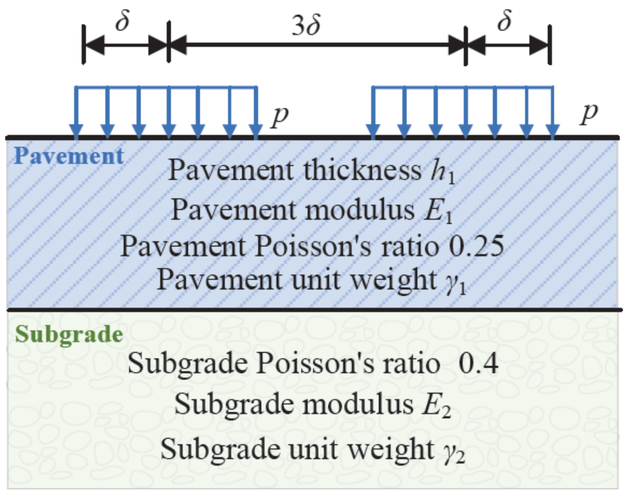


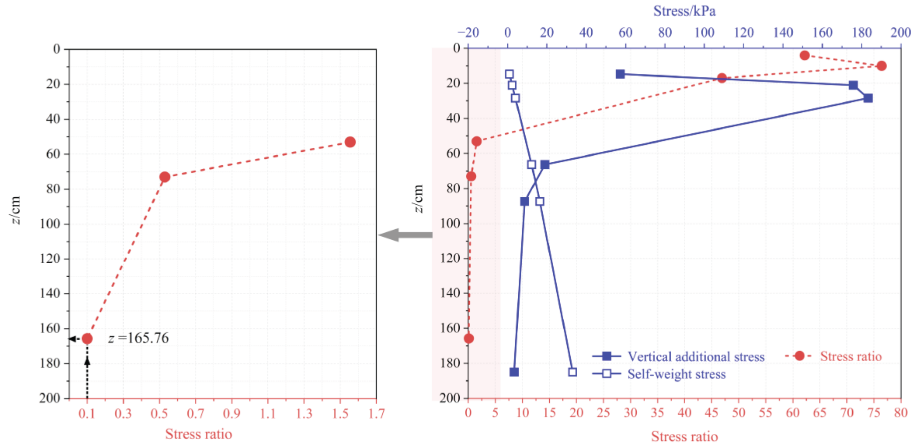
Figure 7: Two-layer pavement-subgrade structure under single-axle dual-wheel load.

Considering that the reliability of the WorkAround program had not yet been verified, the numerical example presented in Section 3.2 was adopted as the reference case. The distributions of vertical additional stress, self-weight stress, and stress ratio along the depth beneath the center of the dual-wheel gap were obtained. A comparison of the results obtained from the WorkAround and GAMES programs is shown in Figure **8**. Two points should be noted here:

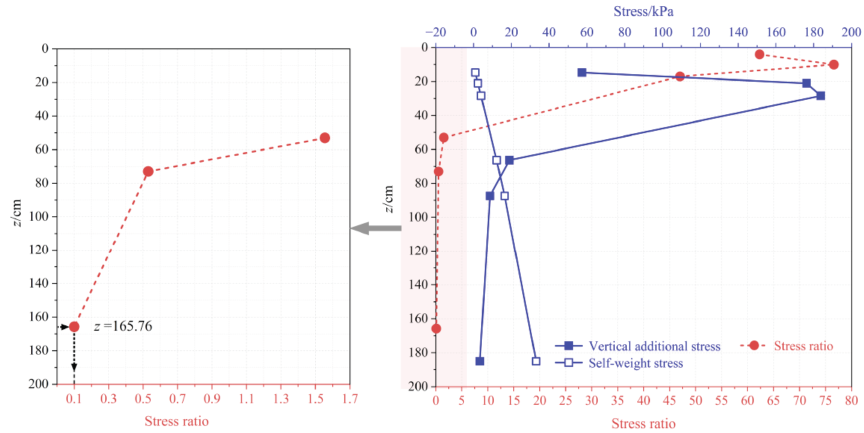
(1) The GAMES program can only provide the additional stress. The self-weight stress shown in Figure **8(b)** was calculated manually by the authors based on the depth of each calculation point and the unit weight of the structural layers.

(2) To facilitate a better parallel comparison, the two subfigures in Figure **8**, i.e., (a) and (b), adopt exactly the same coordinate scales.

It can be observed that the results obtained from the two programs are in excellent agreement. The



(a) WorkAroumd



(b) GAMES

Figure 8: Comparison of the results obtained from the WorkAround and GAMES programs.

subgrade workaround (depth below the top of the subgrade) calculated by the WorkAround program is 92.76 mm, which means the subgrade workaround depth (depth below the pavement surface) is 165.76 cm. The stress ratio at the depth of 165.76 cm below the pavement surface obtained from GAMES is also exactly 0.1, which fully demonstrates that the WorkAround program is completely reliable for calculating the subgrade workaround.

4.1.2. Parameter Discussion

For the six influencing factors, namely, pavement modulus, pavement unit weight, subgrade unit weight, pavement thickness, subgrade modulus, and axle load, the corresponding value ranges are established with reference to the specific requirements of specifications and practical engineering experience, and values are taken at equal intervals within these ranges, as presented in Table **2**.

For the special influencing factor of axle load, this paper simplifies the axle load into an equivalent circular uniformly distributed load based on the equivalent circle radius conversion formula [Equation (16)] and the relationship between wheel load F and load contact pressure p proposed by Heukelom and Klomptichude [Equation (17)], with the standard wheel load as the reference. The specific values are listed in Table **3**.

Table 2: Values of each Influencing Factor

Influencing factors	Values 1	Values 2	Values 3	Values 4	Values 5
Subgrade modulus E_2/MPa	30	40	50	60	70
Pavement modulus E_1/MPa	1000	1125	1250	1375	1500
Pavement thickness h_1/cm	60	70	80	90	100
Pavement unit weight γ_1/kN·m^{-3}	20	21	22	23	24
Subgrade unit weight γ_2/kN·m^{-3}	16	17	18	19	20
Axle load P/kN	100	125	150	175	200

Table 3: Load Parameters under Different Axle Loads

Load parameters	Values 1	Values 2	Values 3	Values 4	Values 5
Axle load *P*/kN	100	125	150	175	200
Single-wheel load *F*/kN	25	31.25	37.5	43.75	50
Contact pressure *p*/MPa	0.7	0.75	0.8	0.84	0.88
Load radius δ /cm	10.65	11.51	12.2	12.87	13.44
Wheel center-to-center distance 3 δ /cm	31.95	34.53	36.6	38.61	41.22

$$\delta = \sqrt{\frac{10F}{\pi p}} \tag{16}$$

$$\frac{p_i}{p_j} = \sqrt[3]{\frac{F_i}{F_j}} \tag{17}$$

For all six influencing factors, values 3 is adopted as the baseline model. The control variable method is then applied, and single-variable calculations are performed using the WorkAround program based on the baseline model. The scatter plots with connecting lines for each influencing factor versus the subgrade workaround are obtained, as shown in Figure **9**. It is evident that pavement modulus, pavement unit weight, subgrade unit weight, and pavement thickness are negatively correlated with the subgrade workaround, while

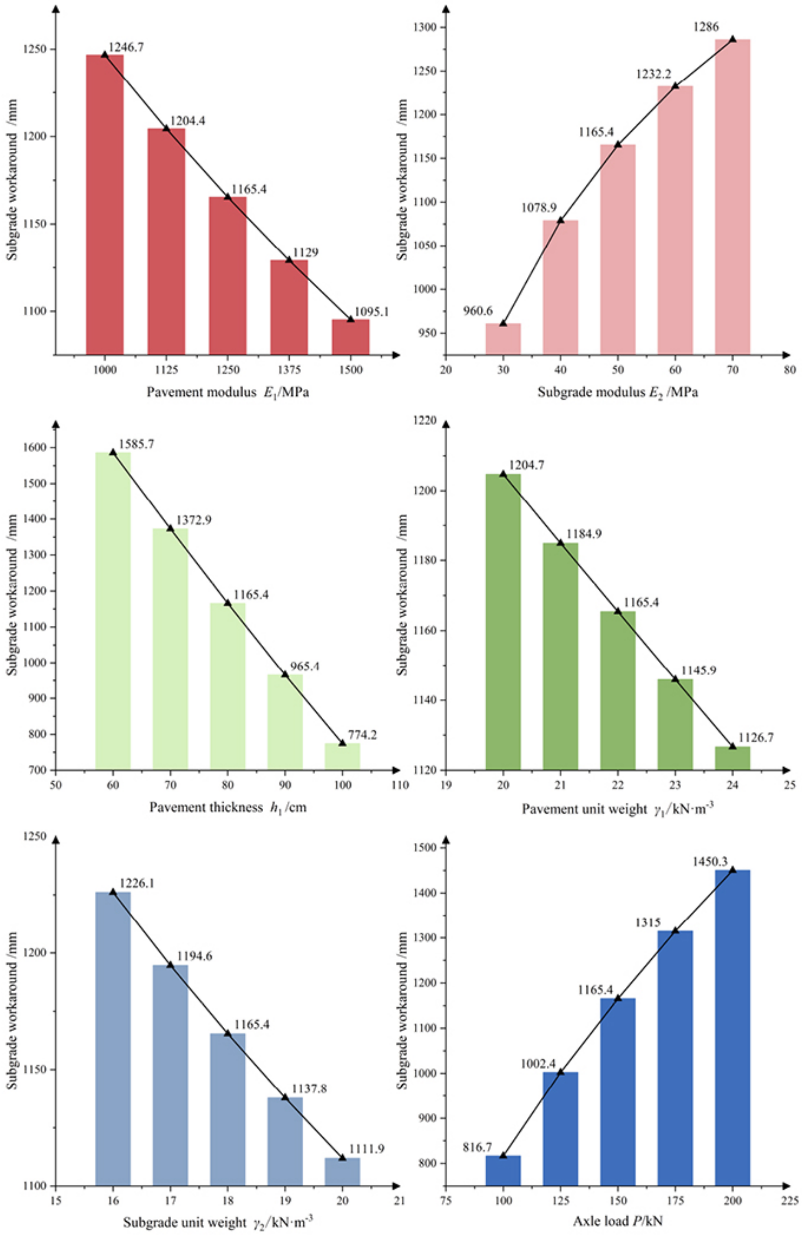


Figure 9: Positive and negative correlations between influencing factors and the subgrade workaround.

subgrade modulus and axle load are positively correlated with the subgrade workaround.

It is worth noting that the conclusion that the subgrade workaround is positively correlated with the subgrade modulus was once considered somewhat questionable. However, after designing and conducting further numerical experiments, we consider that the positive correlation between the subgrade workaround and the subgrade modulus is attributable to the fact that, at the same calculation point within the subgrade, the vertical additional stress is positively correlated with the subgrade modulus. In fact, a similar conclusion was also reported in Reference [17]. As shown in Figure **10**, for a two-layer system where E_1/E_2 is the ratio of pavement modulus to subgrade modulus, q is the load, a is the radius of the loaded area, both Poisson's ratios are taken as 0.5, and h_1/a=1, it is evident that the vertical additional stress σ_z increases with increasing subgrade modulus E_2.

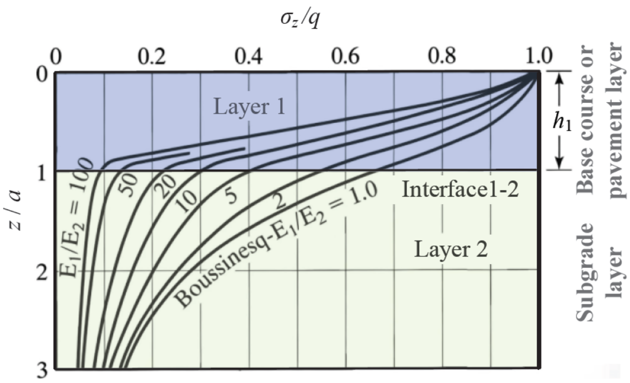


Figure 10: Vertical stress distribution in a two-layer system (modified from [17]).

4.2. Influence Degrees of Parameters Related to the Subgrade Workaround

4.2.1. Determination of the Orthogonal Experimental Design Scheme

It should be noted that although the preceding analysis has revealed the relationships between the subgrade workaround and each influencing factor, the dimensions and value ranges of these factors are not uniform. Therefore, only the positive or negative correlations between these factors and the subgrade workaround can be determined, while the relative strength of these correlations remains unknown. To reveal the magnitude of the influence of each factor, three levels are selected for each influencing factor, and a 6-factor, 3-level orthogonal experiment is conducted. A range analysis is then performed to obtain the ranking of the influence degrees. The values are listed in Table **4**.

4.2.2. Analysis and Discussion of Results

Using the $L_{27}(3^{13})$ orthogonal array, the subgrade workaround under 27 different conditions is calculated through the WorkAround program, as shown in Table **5**.

The data are imported into MATLAB for range analysis and error variance calculation, followed by analysis of variance (F-test). The results are presented in Tables **6** and **7**.

The results of the analysis of variance indicate that, within the parameter levels and computational conditions adopted in this study, the P-values of all factors are less than 0.001 (displayed as 0 in MATLAB), and the F-values all exceed the critical value for the significance test. This indicates that variations in the levels of different factors have a significant influence on the subgrade workaround response. Among them, the pavement thickness h_1 exhibits the largest F-value (F = 3391.84), followed by the axle load P (F = 2097.57) and the subgrade modulus E_2 (F = 298.24), indicating that, within the parameter range considered in this study, the pavement thickness has the most significant influence on the subgrade workaround response.

The results of the range analysis are generally consistent with those of the analysis of variance. The ranking of the influence degrees of the factors on the subgrade workaround is as follows: pavement thickness > axle load > subgrade modulus > pavement modulus > subgrade unit weight > pavement unit weight. Among them, the pavement thickness exhibits the largest range, indicating that it is the most sensitive factor affecting the subgrade workaround response

Table 4: Six Factors and Three Levels

Influencing factors	Level 1(L1)	Level 2(L2)	Level 3(L3)
Subgrade modulus E_2/MPa	40	50	70
Pavement modulus E_1/MPa	1000	1250	1500
Pavement thickness h_1/cm	60	80	100
Pavement unit weight γ_1/kN·m^{-3}	20	22	24
Subgrade unit weight γ_2/kN·m^{-3}	16	18	20
Axle load P/kN	100	150	200

Table 5: Subgrade Workaround Calculated under Each Condition

No.	Subgrade modulus E_2/MPa	Pavement modulus E_1/MPa	Pavement thickness h_1/cm	Pavement unit weight γ_1/ kN·m^{-3}	Subgrade unit weight γ_2/ kN·m^{-3}	Axle load P/kN	Subgrade workaround /mm
1	40	1000	60	20	16	100	1317.4
2	40	1000	60	20	18	150	1613.6
3	40	1000	60	20	20	200	1821.4
4	40	1250	80	22	16	100	773.7
5	40	1250	80	22	18	150	1078.9
6	40	1250	80	22	20	200	1298.7
7	40	1500	100	24	16	100	250
8	40	1500	100	24	18	150	542.7
9	40	1500	100	24	20	200	764.6
10	50	1000	80	24	16	150	1269
11	50	1000	80	24	18	200	1495.7
12	50	1000	80	24	20	100	819.7
13	50	1250	100	20	16	150	869.5
14	50	1250	100	20	18	200	1095.3
15	50	1250	100	20	20	100	476.5
16	50	1500	60	22	16	150	1609.4
17	50	1500	60	22	18	200	1822.6
18	50	1500	60	22	20	100	1116.2
19	70	1000	100	22	16	200	1344.3
20	70	1000	100	22	18	100	664.5
21	70	1000	100	22	20	150	960.2
22	70	1250	60	24	16	200	2027.3
23	70	1250	60	24	18	100	1288.2
24	70	1250	60	24	20	150	1581.9
25	70	1500	80	20	16	200	1624.9
26	70	1500	80	20	18	100	910.5
27	70	1500	80	20	20	150	1203

Table 6: Range Analysis of Influencing Factors

Rank	Influencing factors	Range /mm	Mean of L1 /mm	Mean of L2/mm	Mean of L3/mm
1	Pavement thickness h_1	803.38	1577.56	1163.79	774.18
2	Axle load P	630.90	846.30	1192.02	1477.20
3	Subgrade modulus E_2	238.20	1051.22	1174.88	1289.42
4	Pavement modulus E_1	162.43	1256.20	1165.56	1093.77
5	Subgrade unit weight γ_2	115.92	1231.72	1168.00	1115.80
6	Pavement unit weight γ_1	99.22	1214.68	1185.39	1115.46

Table 7: Error Analysis of Influencing Factors

Influencing factors	Sum of squares /mm^2	Mean square /mm^2	*F*-value	*P*-value
Pavement thickness h_1	2905246.58	1452623.29	3391.84	0.0000
Axle load P	1796655.09	898327.54	2097.57	0.0000
Subgrade modulus E_2	255451.10	127725.55	298.24	0.0000
Pavement modulus E_1	119263.94	59631.97	139.24	0.0000
Subgrade unit weight γ_2	60669.97	30334.98	70.83	0.0000
Pavement unit weight γ_1	46780.68	23390.34	54.62	0.0000

within the scope of this analysis, whereas the pavement unit weight shows the smallest range, indicating a relatively weak influence.

It should be emphasized here that the aforementioned macroscopic conclusions are limited to the specific method adopted for determining the subgrade workaround and the parameter value ranges set in the numerical example. For other determination methods or cases beyond the adopted parameter value ranges, further careful examination is required.

4.3. Practical Implications for Engineering Design

The influence trends of various factors on the subgrade workaround and the ranking of their correlation strengths obtained above are of important guiding significance for the design of asphalt pavements for new highways. In asphalt pavement design, the positional relationships among the subgrade workaround, the groundwater table, and the capillary wetting surface need to be determined in order to identify the subgrade moisture condition, and subsequently to estimate the moisture adjustment coefficient for the subgrade resilient modulus, thereby obtaining the design value of the subgrade resilient modulus for new highways. For actual engineering projects, the capillary wetting surface and the groundwater table are already determined, and the design axle load for new asphalt pavement design is also fixed. Moreover, it is stipulated in the specification that the roadbed of new highways should be in a dry or moderately moist condition [1]. Obviously, the subgrade workaround of the highway needs to be appropriately reduced. This can be achieved through the following technical approach:

First, in view of the positive or negative correlations between the influencing factors and the subgrade workaround, it is necessary to increase the pavement modulus, pavement unit weight, subgrade unit weight, and pavement thickness, while decreasing the subgrade modulus. Then, considering the ranking of the influence degrees of each factor on the subgrade workaround: pavement thickness > axle load > subgrade modulus > pavement modulus > subgrade unit weight > pavement unit weight, it is evident that increasing pavement thickness and reducing subgrade modulus are the two most effective measures.

However, the approach of reducing the subgrade modulus through material selection is not highly operable, and from a comprehensive perspective, the subgrade modulus should not be too low. Therefore, in actual engineering practice, it is more advisable to reduce the subgrade workaround by increasing pavement thickness or improving pavement modulus (e.g., by using high-modulus asphalt mixtures). It should also be noted that the aforementioned significance analysis was conducted based on a two-layer structural system, in which the simplified pavement structure actually comprises the surface course, base course, and subbase course. Therefore, if an increase in pavement thickness is needed, a feasible approach is to appropriately increase the thickness of the base course or subbase course, which can reduce the subgrade workaround while also lowering costs, thereby achieving a sound balance between technical performance and economy.

It should be noted that the aforementioned conclusions regarding the influence patterns of various factors on the subgrade workaround and the ranking of their correlation strengths are all derived within the macroscopic framework in which the subgrade workaround is determined by the ratio of additional stress to self-weight stress. Readers should keep this in mind when applying these conclusions.

5. CONCLUSIONS

(1) The current mainstream methods for determining the subgrade workaround are summarized, and their characteristics are compared and analyzed. The method explicitly defined in the *Specifications for Design of*

Highway Subgrades, which adopts the criterion that the ratio of the vertical stress induced by wheel loads to the vertical compressive stress caused by the self-weight of the overlying layers exceeds 0.1, is widely recognized, extensively applied, and relatively convenient in calculation.

(2) Based on the GAMES program, the distribution characteristics of the ratio of vertical additional stress to self-weight stress are obtained. The stress ratio decreases with increasing depth and exhibits a curvilinear pattern. The calculated subgrade workaround depth varies with different horizontal positions, with the greatest depth occurring directly beneath the center point of the wheel gap. Although the stress ratio limits increase in arithmetic progression, the subgrade workaround depth does not follow the same arithmetic progression.

(3) The subgrade workaround under various conditions is obtained using the WorkAround program, and the positive and negative correlation trends between the influencing factors and the subgrade workaround are identified, i.e., pavement modulus, pavement unit weight, subgrade unit weight, and pavement thickness are negatively correlated with the subgrade workaround, while subgrade modulus and axle load are positively correlated with the subgrade workaround.

(4) Through orthogonal experimental design, the subgrade workaround under various conditions is obtained using the WorkAround program, and the ranking of the influencing factors in terms of their correlation with the subgrade workaround is identified as: pavement thickness > axle load > subgrade modulus > pavement modulus > subgrade unit weight > pavement unit weight.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

AVAILABILITY OF DATA AND MATERIAL

Data will be made available on request.

CODE AVAILABILITY

Not applicable.

AUTHORS' CONTRIBUTIONS

Xin Jiang: Supervision, Conceptualization, Methodology, Writing. **Xinya Huang**: Software, Data curation, Writing – original draft. **Yang Xue**: Software, Investigation. **Hongpo Liu**: Writing – review & editing. **Yanjun Qiu**: Investigation.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

We hereby confirm that all necessary ethics approval and informed consent have been obtained for the research conducted, in accordance with institutional and ethical guidelines.

CONSENT FOR PUBLICATION

We hereby confirm that we have obtained the necessary consent for publication from all relevant parties involved in this work, and we declare that we have the right to publish this material.

REFERENCES

[1] CCCC Second Highway Consultants Co., Ltd. JTG D30-2015 Specifications for design of highway subgrades [S]. Beijing: China Communications Press Co., Ltd. 2015.

[2] Yu XJ, Long HJ. A study on influencing factors of subgrade workaround [J]. Highway 2012(9): 33-37.

[3] Li X H, Hu J M, Shi D J, *et al*. Calculation and analysis of the depth of rock-soil filled subgrade working area in highway [J]. Subgrade Engineering 2018(2): 42-46.

[4] Fang ZY. Subgrade engineering[M]. Beijing: China Communications Press 1987.

[5] Second Highway Survey and Design Institute of the Ministry of Transport. Highway design manual: subgrade [M]. 2nd ed. Beijing: China Communications Press 1996.

[6] Huang XM. Subgrade and pavement engineering[M]. 8th ed. Beijing: China Communications Press Co., Ltd. 2025.

[7] Zhou ZF, Miao LW, Sun C. Analysis of subgrade influence depth and its influencing factors based on strain [J]. Journal of Wuhan University of Technology (Transportation Science & Engineering) 2016; 40(1): 41-44.

[8] Lu Z, Wang CB, Fu JJ, *et al*. Research on influence depth of road subgrade induced by vehicle loads [J]. Rock and Soil Mechanics 2013; 34(2): 317-322.

[9] Song Y, Wei LY, Feng L. Research on subgrade workaround depth of semi-rigid pavement under dynamic vehicle load[J]. Journal of China and Foreign Highway 2015; 35(6): 47-52.

[10] Yan SJ, Liu JH, Yang ZZ, *et al*. Research on subgrade workaround depth of asphalt pavement[J]. Journal of China and Foreign Highway 2018; 38(5): 14-18.

[11] Huang QL, Ling JM. Methodology study on defining subgrade's working area [J]. Journal of Tongji University (Natural Science) 2011; 39(4): 551-555.

[12] Zhao GS. Study on the depth of subgrade work area of grade road under excess traffic load [D]. Jinan: Shandong University 2009.

[13] Zhu HB, Jia ZX, Zhang HB, *et al*. Discussion of the definition of subgrade workspace under heavy traffic [J]. Journal of Highway and Transportation Research and Development 2009; 26(1): 39-44.

[14] Tong SJ, Cai JJ, Xin Q, *et al*. Research on workspace depth of roadbed with consideration of pavement structure [J]. Highway 2012(10): 24-27.

[15] Li C, Guan SF. Establishment of the depth of subgrade working area in asphalt pavement [J]. Journal of Transport Science and Engineering 2011; 27(2): 11-15.

[16] Li L. Computational analysis on depth of subgrade working area and the application [J]. Subgrade Engineering 2015(6): 140-143.

[17] Huang YH. Pavement analysis and design[M]. 2nd ed. Upper Saddle River: Pearson Prentice Hall 2003.

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