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INFLUENCE OF NONLINEAR ANALYSIS TECHNOLOGY ON DAMAGE ANALYSIS OF ASPHALT PAVEMENT STRUCTURE

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Abstract. As a means of predicting the damage pattern and design life of asphalt pavement structures, the reliability of damage analysis is highly dependent on the calculation accuracy of the pavement mechanical responses under wheel load. The nonlinear analysis, on its part, can practically describe the stress dependence of the modulus of granular materials and fine-grained soils, so that the mechanical responses of the wheel-loaded asphalt pavement structure can be obtained more accurately. Therefore, the correct application of nonlinear analysis technology is essential to obtain reliable damage analysis results. For this reason, computer program KENLAYER was utilized to explore the effects of stress adjustment methods and core parameters of nonlinear iterative analysis on the damage analysis results. According to the calculation results, this paper explains the reasons why the stress adjustment Methods 2 and 3 are not applicable to the structural analysis of pavements containing nonlinear granular materials in the case of thin surface layers, illustrates the effects of

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improper selection of the adjustment methods and each iteration parameter on the dominant damage pattern, finds out the reasons for unreliable calculation results due to improper selection of the iteration parameters, and makes corresponding suggestions for carrying out damage analysis accurately.

Keywords: asphalt pavement structure, damage analysis, iterative convergence, nonlinear, stress adjustment.

Introduction

As an effective means of predicting the damage form of pavement structures and design life using the mechanical response at critical locations of asphalt pavements, there have a plenty of relevant studies on the topic of damage analysis. These topics are mostly focused on the proposal of performance models (AI, 1982; Grivasand Shen, 1991; Tutu and Kimm, 2022; etc.), the determination of transfer function coefficients (Shook et al., 1982; Craus et al., 1984; Zhao and Wang, 2021), and the conduction of damage analysis using specific performance models for a specific condition (Zhou, 2019; Perez-Gonzalez et al., 2021; Ye, 2022; etc.). However, the possible damage analysis errors

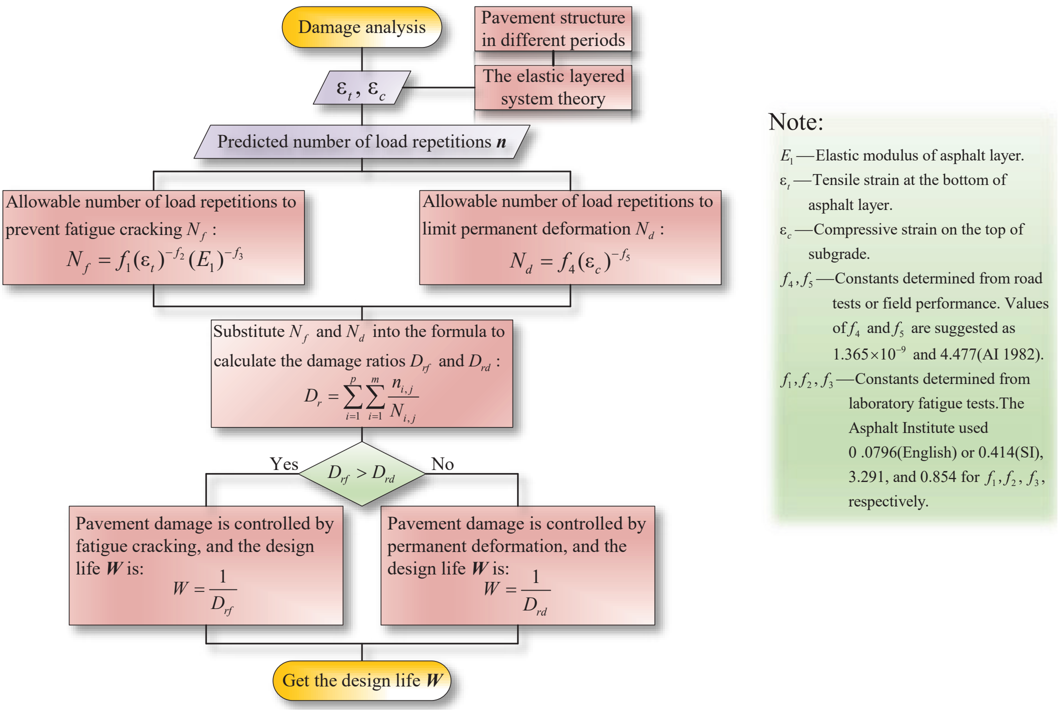

Figure 1. Damage analysis process

caused by the mechanical response calculation often cannot be given enough attention. It should be noted that the transfer functions in these performance models mostly involve exponential operations, take the AI (1982), Huang (2004) analysis model as an example, as shown in Figure 1, tensile strain at the bottom of asphalt layer ε_t and the vertical compressive strain on the top of the subgrade ε_c which actual values are often not large (10^{-4}–10^{-6}) (Alireza, 2016; Abubeker and Sigurdur, 2017; Pan et al., 2021), are amplified by exponential coefficients f_2, f_3 or f_5 whether the pavement is controlled by fatigue cracking of asphalt surface layer or permanent deformation of subgrade. The small differences in strain may also lead to large deviations in the calculation of N_d and N_f, which in turn affects the authenticity of the damage analysis.

In view of the strong dependence of damage analysis on the calculation results of mechanical responses, it is obvious that the direct application of linear elastic layered computer programs, such as BISAR (De Jong et al., 1979), GAMES (Maina and Matsui, 2004), etc., to the calculation of pavement structures with nonlinear materials such as granular materials and fine-grained soils will inevitably affect the calculation results of mechanical response and thus the reliability of damage analysis. Therefore, in order to obtain accurate mechanical response, it is necessary to introduce nonlinear analysis that can describe the material more realistically during the damage analysis. With regard to the structural nonlinear analysis of asphalt pavements, most of the existing research has focused on several aspects. (1) The proposed material model of the nonlinear layer resilient modulus as influenced by the stress state and the determination of material parameters (Seed et al., 1967; Uzan, 1985; Thompson and Robnett, 1979; Shi et al., 2021). (2) How nonlinear material models are embedded in computer programs (i.e., design and development of a computer program for nonlinear analysis of asphalt pavement structures). Representative work can be found in Huang (1993), Huang (2004) corresponding to KENLAYER, Sivaneswaran et al. (2001) corresponding to EverStress, Erlingsson and Abubeker (2013) corresponding to ERAPAVE, Brundaban et al. (2020) corresponding to CrossPave and so on. (3) Nonlinear analysis of specific asphalt pavement structures to obtain the mechanical response under wheel load. Representative work in this area can be found in very many related articles such as Ziari and Khabiri (2007), Ebels (2008), Kuna et al. (2018), Jiang et al. (2019, 2020), Kuchiishi et al. (2021). These works rarely involve the organic combination of nonlinear analysis and damage analysis. Although KENLAYER, a classical computer program based on the elastic layered system theory (Timoshenko and Goodier, 1951; Huang, 1967, 1968), has introduced damage analysis, the available literature, manuals, and help documents do not specify how to accurately use nonlinear analysis to perform damage analysis.

Therefore, this paper chooses to rely on the KENLAYER program to illustrate the whole nonlinear damage analysis process with its high openness, in order to find the unfavourable factors that may affect the damage analysis and improve the reliability of the damage analysis of asphalt pavement structure when it contains nonlinear layers.

1. Nonlinear stress adjustment methods and nonlinear iterative process

1.1. Principle brief introduction

Compared with fine-grained soil, granular material is more complicated to deal with in the KENLAYER program due to stress adjustment (Huang, 2004), so this paper mainly discusses the nonlinear granular material. The flow chart for nonlinear iterative calculation of granular material and the three stress adjustment methods for granular material are shown in Figures 2 and 3, respectively.

As can be seen in Figures 2 and 3, all three methods use the same iterative method, in other words, determine stress points, calculate the mechanical response at the stress point according to the elastic layered system theory, substitute these mechanical responses into K–θ model (Seed et al., 1967; Dehlen and Monismith, 1970; Hicks and Monismith, 1971) to get new elastic modulus, and repeat this process until actual number of iterations reaching ITENOL or convergence accuracy meeting DELNOL.

While the differences between the three methods mentioned above are mainly reflected in: (1) Method 1 divides the entire granular layer into several sub-layers and uses multiple stress points for calculation, while Methods 2 and 3 use only one stress point in the entire granular layer. (2) The adjustment process of the three methods is not consistent, which is mainly reflected by the stress adjustment parameter PHI, Method 1 sets PHI to 0 or 90 to adjust the possible calculated tensile stress (negative value) to 0. Generally, tension does not appear at the stress point for Method 2. It sets PHI to K_1 from K–θ model to give a lower limit of the elastic modulus calculated by iteration. In this case the PHI unit is psi or kPa. Method 3 is based on the Mohr-Coulomb adjustment model (Raad and Figueroa, 1980), where PHI represents the angle of internal friction (°) generally set to 40–60, and in Method 3 the

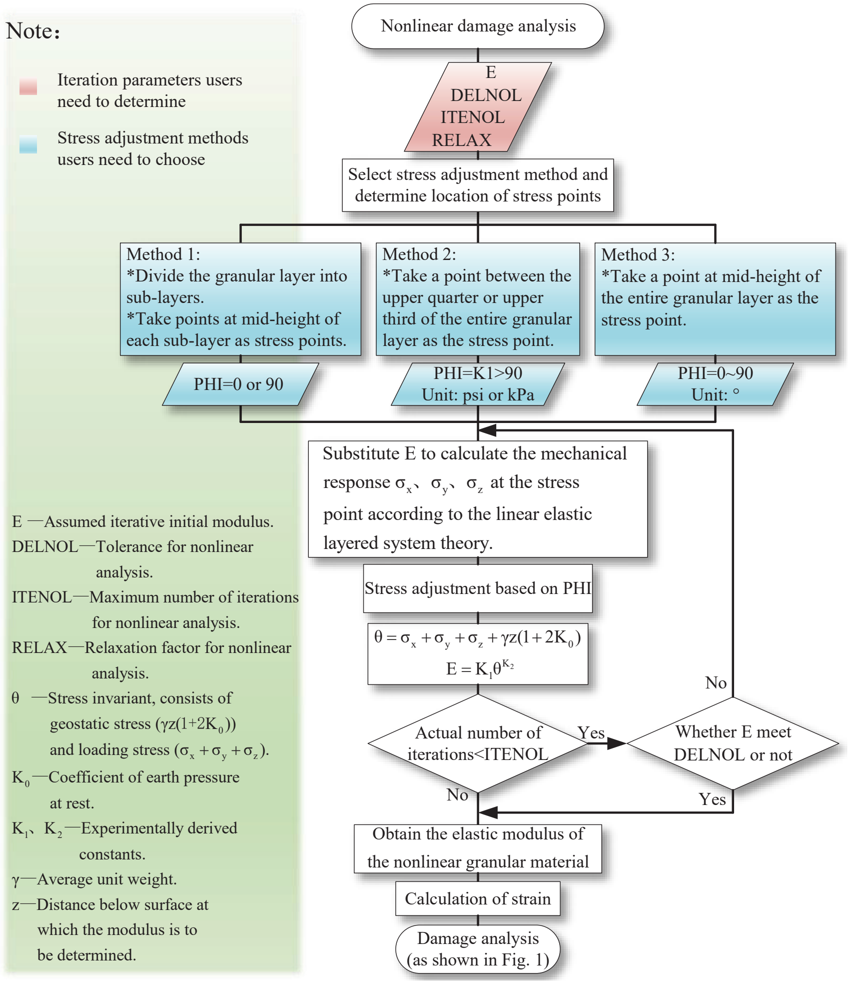

Figure 2. The process of determining the elastic modulus of nonlinear granular material

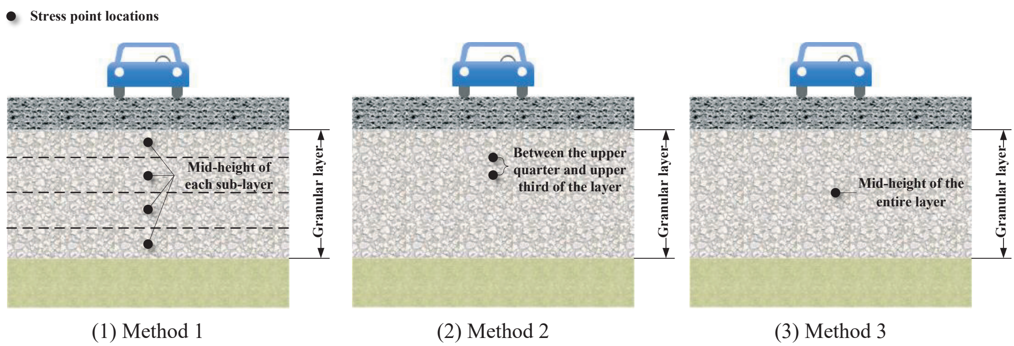

Figure 3. Three stress adjustment methods

horizontal stress is adjusted according to the calculated vertical stress at the stress point. (3) Besides, it should be noted that the vertical positions of the stress points corresponding to the three adjustment methods are different, but their plane positions are the same.

1.2. Discussion

From the flow chart mentioned above, it is easy to see that the stress adjustment methods (division of structural layers, selection of parameters PHI), iterative parameter settings (including assumed iterative initial modulus E, tolerance for nonlinear analysis DELNOL, maximum number of iterations for nonlinear analysis ITENOL, relaxation factor for nonlinear analysis RELAX) are needed to be determined by the user. While the program is undoubtedly flexible in this way, there is another problem that cannot be ignored, namely, if not properly selected, it may directly lead to deviations in the modulus obtained by iteration, which in turn may lead to errors in the subsequent mechanical response calculation and damage analysis. Although the program provides default values or recommended values for the above parameters, again none of them is explicitly stated why these values are selected in this way.

Therefore, it is advisable to take the two modules of stress adjustment methods and iteration parameter setting as entry points to explore the specific causes of damage analysis errors from the perspective of elastic modulus obtained by iteration, and to give corresponding suggestions on the selection of adjustment methods and iteration parameters, so as to improve the reliability of damage analysis of asphalt pavement structures when containing nonlinear layers.

2. Nonlinear granular layer analysis error and its reducing strategies

2.1. Errors caused by improper selection of adjustment methods

Huang (2004) once carried out a three-layer system analysis of asphalt surface layer-granular layer-subgrade by the KENLAYER program to compare the calculation results of ε_t and ε_c with the axisymmetric nonlinear finite element program MICHPAVE (Harichandran et al., 1990). The comparison shows that the results of Methods 2 and 3 are quite different from the results calculated by

MICHPAVE when the asphalt surface layer is thin or without asphalt surface layer, while Method 1 is relatively consistent and its results are little affected by the thickness of the asphalt surface layer. This means that Methods 2 and 3 are only applicable to the case where the asphalt surface layer is thick. However, Huang (2004) did not give a deeper explanation for this conclusion, which needs to be discussed in detail.

2.1.1. The establishment of analytical model

Referring to Huang (2004), a three-layer system shown in Figure 4 is established for further discussion on damage analysis. From top to bottom, the structure consists of hot mix asphalt surface layer HMA (Variable), granular layer (30.48 cm) and subgrade. It is assumed that the interface between each layer is continuous, and for the purpose of highlighting the analysis, except for the granular layer which is assumed to be nonlinear, other layers are considered as linear elastic layers, its elastic modulus E, Poisson's ratio μ, unit weight γ, as well as the relevant parameters of the granular layer regarded as $K–\theta$ model, the load-related

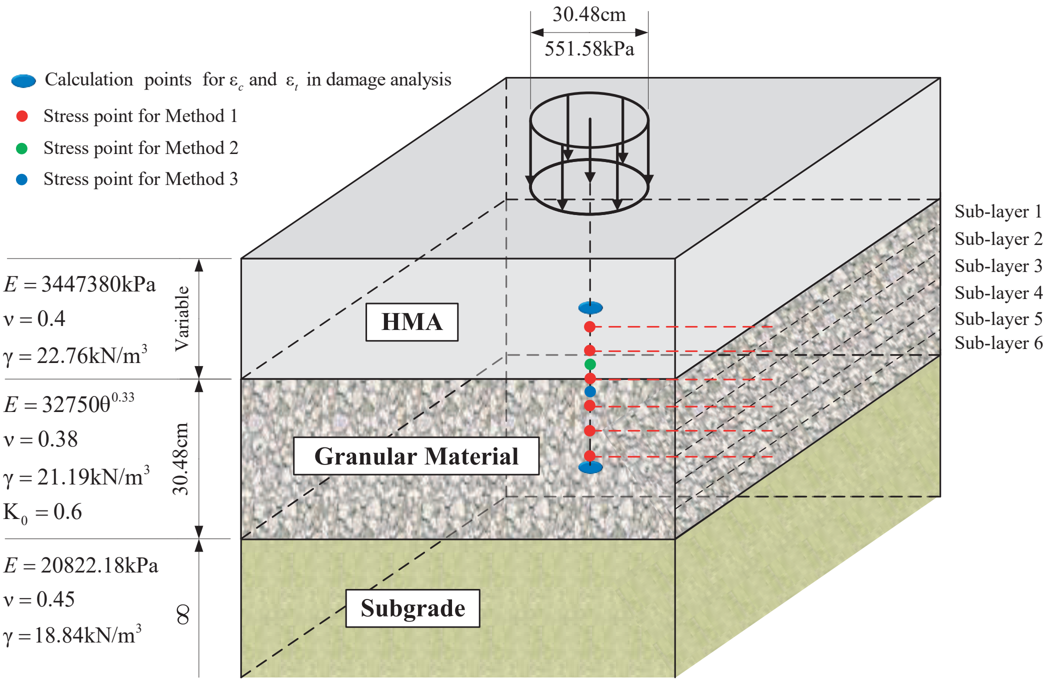

Figure 4. Three-layer system composed of asphalt surface layer + granular layer + subgrade

parameters and the vertical position of the stress point of the three methods are all listed in Figure 4. For single wheel load, the horizontal position of the stress point should be taken at the wheel centre.

Three methods are used to calculate ε_t and ε_c for different asphalt surface layer thicknesses. In Method 1, the 30.48-cm granular layer is divided into six layers (Sub-layer 1 to Sub-layer 6) with the stress points at the mid-height of the sub-layer, each 5.08 cm thick, and PHI = 0. In Method 2, the granular layer is considered to be a single 30.48-cm layer with the stress point at the upper third of the layer, and PHI = 32750 kPa. In Method 3, the granular layer is considered to be a single 30.48-cm layer with the stress point at the mid-height of the layer, and PHI = 40°. In addition, the iteration parameters are set as default or recommended values, that is to say E = 32750 kPa, DELNOL = 0.01, ITENOL = 15, and RELAX = 0.5. The predict number of load repetitions is set as n = 1000 times.

2.1.2. Analysis and comparison of the calculation results by three adjustment methods

After a series of calculations, the design life calculated by three methods for different asphalt surface layer thicknesses and the deviation rate of the other two methods calculated based on Method 1 are all listed in Table 1.

Table 1 shows that when there is no surface layer or the surface layer is very thin, compared with Method 1, the design life deviation rate calculated by Methods 2 and 3 is extremely large, and the results are obviously distorted. As the thickness of the surface layer increases, the

Table 1. Design life calculated by three methods and deviation rate of Methods 2 and 3 compared to Method 1

Asphalt Layer Thickness, cm	0.00	2.54	5.08	7.62	10.16	20.32	30.48
Design Life, years – Method 1	0.58	1.64	3.32	7.76	19.9	729.02	12034.39
Design Life, years – Method 2	40.44	3.25	5.00	9.38	21.18	736.25	12153.78
Deviation rate	6872.41%	98.17%	50.60%	20.88%	6.43%	0.99%	0.99%
Design Life, years – Method 3	27.62	2.82	5.19	11.13	26.29	795.46	12254.65
Deviation rate	4662.07%	71.95%	56.33%	43.43%	32.11%	9.11%	1.83%

deviations of Methods 2 and 3 continue to shrink. When the thickness of the surface layer exceeds 8 cm and 14 cm, respectively, compared with Method 1, the calculated design life deviation rate of Methods 2 and 3 can be maintained within 20%. For this example, when the thickness of the asphalt surface layer increases from 0.00 cm to 30.48 cm, the design life of the pavement structures is all controlled by the permanent deformation of subgrade.

Furthermore, sort the calculation results of elastic modulus at the end of the iteration of the granular layer, ε_t and ε_c into Figure 5.

The variation of the strain with the thickness of the asphalt surface layer (the 6 curves in Figure 5) shows that ε_t firstly increases and then decreases with the increase of the surface layer thickness. As for ε_c, the three methods show different laws with the increase of the surface layer thickness. The ε_c of Method 1 shows a continuous decrease with the increase of the surface layer thickness, while the ε_c of Methods 2 and 3 firstly increases and then decreases with the increase of the surface layer thickness. Except that Huang (2004) does not consider when the asphalt surface layer thickness is 0, the strain law is consistent with

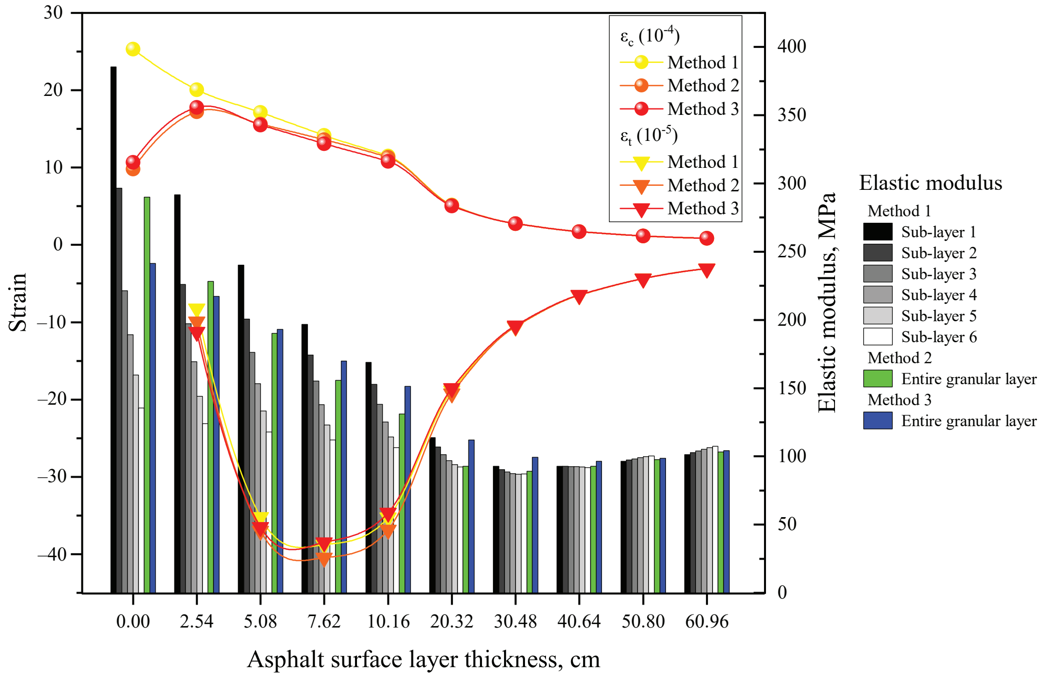

Figure 5. The elastic modulus of the granular layer, ε_t, ε_c calculated by three methods for different asphalt surface layer thicknesses

the conclusion of Huang (2004). Combining Figure 5 with Table 1, it can be found that when the thickness of the surface layer exceeds 2.54 cm, the difference between ε_c corresponding to three methods is not large, but the deviation rate of the design life calculated by Methods 2 and 3 is still very large, which confirms the speculation that a small difference in strain can cause a large deviation in the calculation result of the damage analysis.

The bars in Figure 5 show the elastic modulus distribution at the end of the granular layer iteration. It can be seen that, for Method 1, when the surface layer is thin, the elastic modulus of sub-layers 1 to 6 decreases and the difference between adjacent sub-layers is large. With the gradual increase in the thickness of the surface layer, the difference between the sub-layers gradually decreases until the elastic modulus of the six sub-layers is basically the same. Continuing to increase the thickness, the elastic modulus of sub-layers 1 to 6 turn to increase again, but there is little difference between each sub-layer.

In contrast, Methods 2 and 3 each have only one elastic modulus for the granular layer. When the surface layer is thin, their elastic modulus values are kept within the range of the elastic modulus of sub-layers 1 to 6 of Method 1. When the surface layer is thick enough, the elastic modulus of the granular layers of Methods 2 and 3 are not much different from the elastic modulus of the sub-layers of Method 1. It fully shows that when the surface layer is thin, the elastic modulus of each sub-layer in Method 1 is obviously not directly equivalent to a single elastic modulus for the entire granular layer in Methods 2 and 3. However, after the asphalt surface layer reaches a certain thickness, the elastic modulus of each sub-layer in Method 1 is not very different. At this time, a single elastic modulus can be used for the entire granular layer to be equivalent. This preliminarily confirms the correctness of the conclusion that Methods 2 and 3 are only suitable for thicker asphalt surface.

2.1.3. Further exploration of the modulus change

As far as the specific calculation process of the KENLAYER program is concerned, the law of elastic modulus of the granular layer mentioned above can be explained by the ratio of loading stress and geostatic stress. It can be seen from the K–θ model relationship in Figure 2 that the elastic modulus of the granular layer is affected together by the loading stress and the geostatic stress of the structural layer. For Method 1, the stress invariant θ calculated for different asphalt surface layer thicknesses is sorted into Figure 6. The loading stress after the initial iterative calculation and adjustment and the geostatic stress with the respective changes of the asphalt surface layer thickness are sorted into Figure 7.

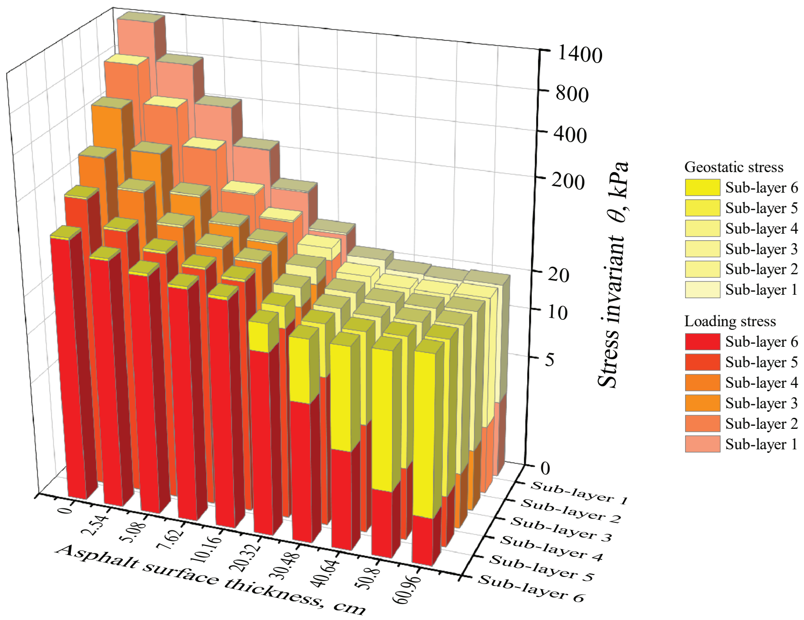

Figure 6. Stress invariant θ corresponding to different asphalt surface thickness

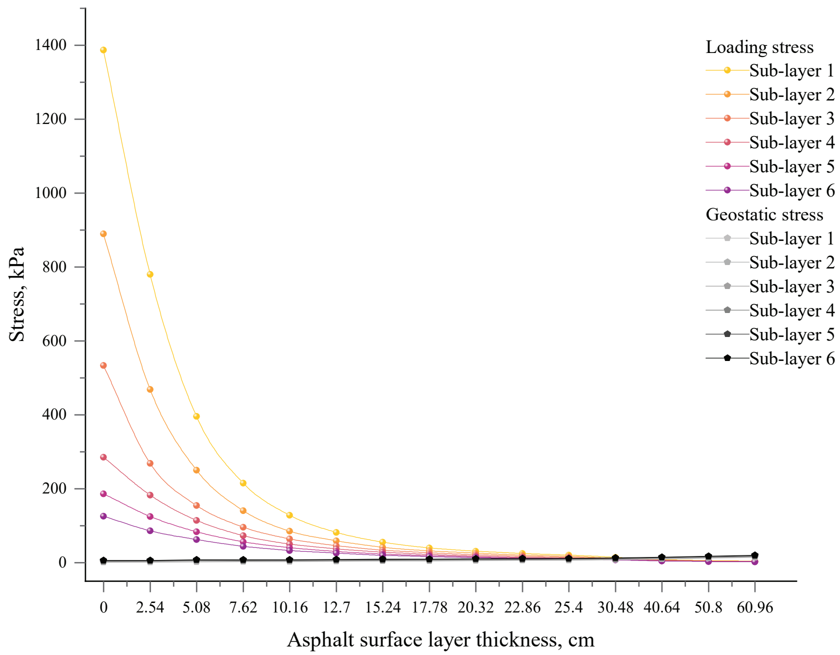

Figure 7. Variation of geostatic stress and modified loading stress with the thickness of asphalt surface layer

Figures 6 and 7 show that:

1. For the same sub-layer, the loading stress first decreases rapidly and then tends to be gentle with the increase of the thickness of the surface layer, while the geostatic stress always maintains a slow linear increase. In this process, the stress invariant θ is first dominated by the loading stress, and its variation law is consistent with the law of the loading stress. As the thickness of the surface layer increases, the stress invariant θ becomes dominated by the geostatic stress, and its law is consistent with the law of geostatic stress.
2. For different sub-layers with the same surface layer thickness, the loading stress of sub-layers 1 to 6 gradually decreases and the decreasing rate gradually slows down, while the geostatic stress increases linearly with little difference between the six sub-layers. The same as (1), when there is no surface layer or the surface layer is thin, the stress invariant θ is dominated by the loading stress, and its variation along the sub-layers 1 to 6 is consistent with the law of the loading stress. As the thickness of the surface layer increases, the stress invariant θ becomes dominated by the geostatic stress, and its law is consistent with the law of geostatic stress.
3. The variation law of the stress invariant θ in Figure 6 is the result of the mutual game between the geostatic stress and the loading stress in Figure 7. For this example, the stress invariant θ gradually changes from being dominated by loading stress to being dominated by geostatic stress when the thickness of the surface layer is 25.4–40.64 cm.

In summary, throughout the analysis it was found that the asphalt surface layer is actually only reflected in terms of thickness and elastic modulus in the KENLAYER model. For Method 1, as long as the depth of the stress point in the granular layer is sufficient, the elastic modulus between the sub-layers of the granular material can maintain a small gap, which actually has nothing to do with the specific material above the granular layer. For a multi-layer system, even if the asphalt surface layer is very thin, as long as there are other structural layers of a certain thickness above the granular layer, the elastic modulus between the sub-layers of the granular material is not much different, and Methods 2 and 3 are also applicable. Therefore, the conclusion obtained by Huang (2004) can be properly extended, in other words, compared to Method 1, Methods 2 and 3 are actually suitable for the situation when any other structural layer (as long as the modulus of the whole layer can be expressed as a fixed value) combination above the granular layer achieve sufficient thickness.

However, Method 1 is not perfect. From the point of view of operability, dividing the sub-layers in Method 1 will appropriately increase the complexity of the modelling prepare process. In contrast, Methods 2 and 3 are relatively convenient and time-saving in large-scale modelling.

2.2. Errors caused by improper setting of iteration parameters

When the three methods mentioned above in KENLAYER program are used to carry out stress adjustment, some of the parameters used for iteration are shared, including E, ITENOL, DELNOL, and RELAX which need to be set by users. It is noted that the KENLAYER program itself lacks a self-reporting capability when performing nonlinear analysis. If these parameters are to be defined improperly, it may also cause the program to fail to obtain the correct results. Therefore, this section intends to combine the specific calculation example of an inverted asphalt pavement, focusing on Method 1, discussing the influence of the above four key parameters on the calculation results, analysing the reasons behind it and rationalizing the values of the corresponding parameters.

2.2.1. Calculated results according to KENLAYER program default and recommended values

According to Wu (2017), it is necessary to build the KENLAYER model of the inverted asphalt pavement structure as shown in Figure 8 to carry out damage analysis and calculate the design life. The pavement structure is HMA (18 cm), asphalt treated base (ATB) (10 cm), graded broken stone (20 cm), low dosage cement stabilized aggregate (20 cm) and subgrade from top to down. The load is 100 kN single-axle double-wheel set, and the predict number of load repetitions is set as n = 10 000 000 times. The interface between each layer is continuous. Except for the graded broken stone layer which is regarded as nonlinear, other layers are all assumed to be linear elastic. Their elastic modulus E, Poisson's ratio μ, unit weight γ, and the nonlinear layer-related parameters of the graded broken stone layer according to the K–θ model, the calculation points corresponding to the damage analysis, and the load-related parameters are all shown in Figure 8.

Choosing Method 1 with relatively higher accuracy for modelling: The 20-cm granular layer is divided into five sub-layers (sub-layers 1 to 5) from the pavement surface downward, each 4 cm thick, and the point at the middle height of each sub-layer is taken as stress points. The iteration parameters are all set by default or recommended values, that is to say E = 24223 kPa, DELNOL = 0.01, ITENOL = 15, and RELAX = 0.5.

After sorting out the calculation results, it can be found that the elastic modulus has already met the convergence accuracy when the actual iteration reaches 9 times, which is less than ITENOL (15 times). The elastic modulus of each sub-layer of the granular layer and the convergence accuracy between two adjacent iterations are shown in Figure 9.

The KENLAYER program defines the convergence accuracy as the ratio of the absolute value of the difference between the elastic modulus of the two adjacent iterations to the elastic modulus of the previous iteration. It is easy to see in Figure 9 that the iteration will stop only when the convergence accuracy of all sub-layers is less than the value of DELNOL (0.01). When some sub-layers satisfy the DELNOL but other sub-layers do not, the sub-layers that satisfy the DELNOL will also

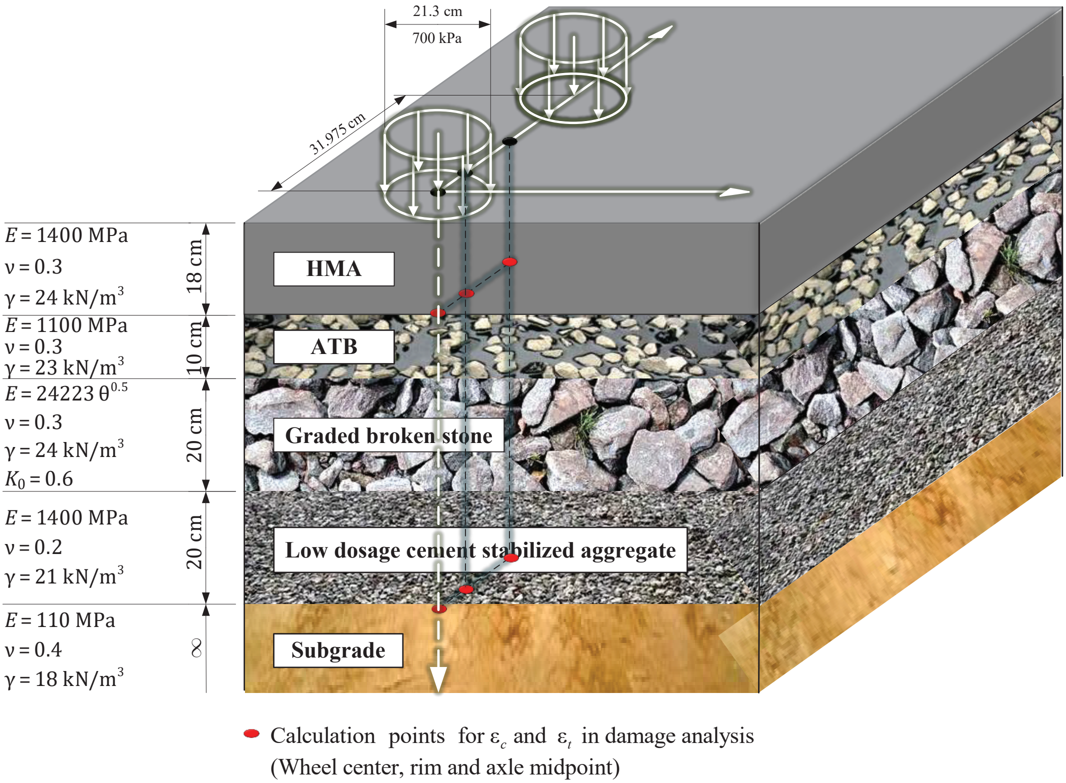

Figure 8. Pavement structure and load

continue to iterate until all sub-layers satisfy the DELNOL. In addition, it is noted that the elastic modulus values of the five sub-layers of the granular layer obtained by the final iteration of this example are not much different, which should be related to the sufficient thickness of the structural layer above the granular layer. This also confirms the conclusion put forward in Section 2.1, i.e., Methods 2 and 3 are only suitable for the situation when any other structural layer combination above the granular layer achieve sufficient thickness.

Substitute the elastic modulus obtained in the 9th iteration into the linear elastic layered system theory to carry out damage analysis, the program outputs the ε_t of -8.95810^{-5} which corresponding to a damage ratio of 1.78610^{-1}, the ε_c of 1.54910^{-4} which corresponding to a damage ratio of 6.41910^{-2}. Therefore, the design life of the asphalt pavement structure is controlled by the asphalt surface layer fatigue cracking, and the design life is 5.6 years.

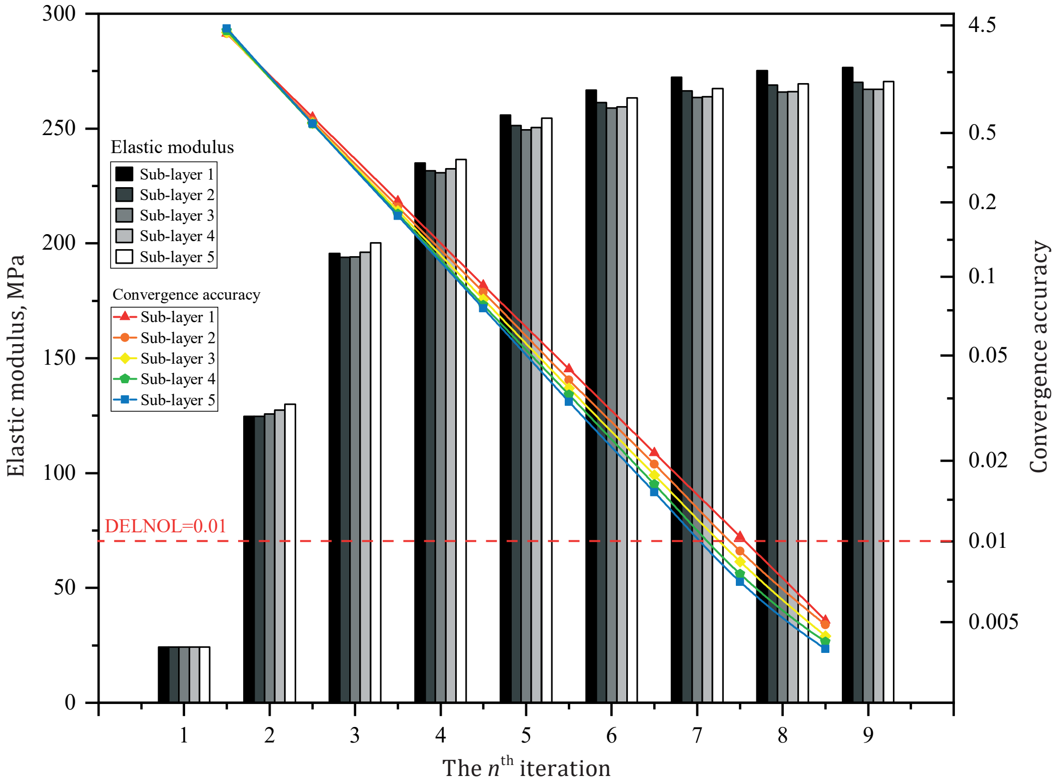

Figure 9. Changes in elastic modulus and convergence accuracy obtained at the n^{th} iteration of each sub-layer

2.2.2. Effects of four iterative parameter changes on damage analysis

In the following, the above results obtained will be used as the standard to carry out parametric analysis on parameters *E*, DELNOL, ITENOL, and RELAX.

(1) Assumed iterative initial modulus E

Changing parameter *E*, let the other iteration-related parameters remain unchanged (ITENOL = 15, DELNOL = 0.01, RELAX = 0.5), and the actual number of iterations and the obtained design life corresponding to different *E* are sorted into Figure 10.

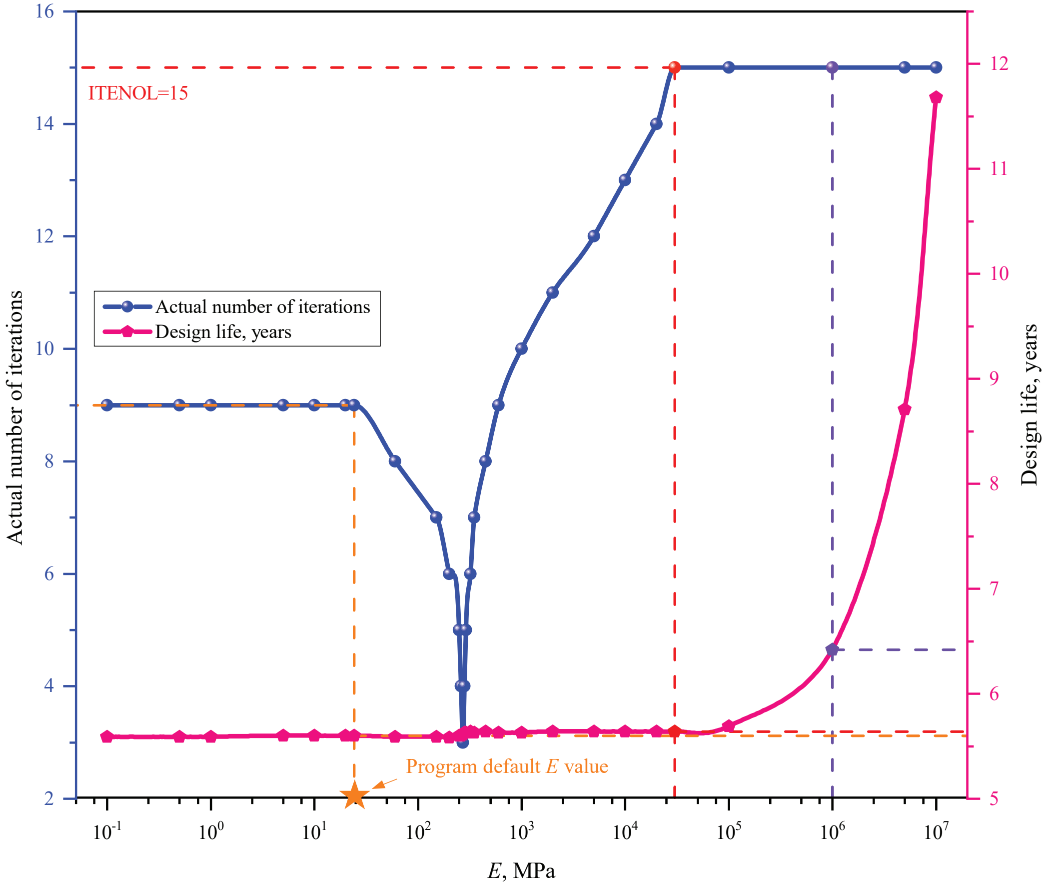

Figure 10. Relationship between *E* and actual number of iterations and design life

As can be seen in Figure 10, parameter E starts from 0 (0 is not desirable) and gradually increases to a larger value. When E is small, the actual number of iterations is always kept at 9. As E gradually increases, the actual number of iterations gradually decreases. When E is close to the final iterative modulus value (the elastic modulus corresponding to the 9th iteration in Figure 9), the actual number of iterations reaches the minimum, after that the actual number of iterations starts to increase again until it reaches the value of the parameter ITENOL (15 times).

During this process, the design life of the asphalt pavement is always controlled by asphalt surface layer fatigue cracking, and when the actual number of iterations is less than 15, the obtained design life is all about 5.6 years, which is consistent with the calculation results in Section 2.2.1. When the actual number of iterations is up to 15, the user needs to manually check whether the final iteration elastic modulus meets the parameter DELNOL. If the DELNOL is met, the calculated design life is also reasonable. If not, it means that the iteration of the program is not fully completed at this time, but the iteration is stopped due to ITENOL. At this time the obtained elastic modulus is unreasonable, the program itself does not report an error, but directly uses the result of the 15th iteration as the final result into the calculation of the subsequent design life.

It can be seen in Figure 10 that the situation that actual number of iterations reaches 15 and the convergence accuracy has not yet met the requirements is relatively extreme. It happens only when E exceeds the correct final iteration result by 4 to 5 orders of magnitude or more. Therefore, the value of E generally does not affect the correctness of the calculation. It is reasonable to set E to a relatively small value such as K_1 without knowing the final iteration result.

(2) Tolerance for nonlinear analysis DELNOL and maximum number of iterations for nonlinear analysis ITENOL

Parameters DELNOL and ITENOL are used to control the loop. It can be seen from the analysis in the previous part that ITENOL is the primary control factor, and DELNOL is the secondary control factor. Within the range of ITENOL, the iteration stops when DELNOL is met. Once ITENOL is reached, the iteration stops immediately regardless of whether DELNOL is met or not.

On the basis of Section 2.2.1, set ITENOL = 20, only change DELNOL, and let the other iteration-related parameters remain unchanged ($E = K_1$, RELAX = 0.5). Figure 11 shows the law of the actual number of iterations and the design life with the change of DELNOL. In the process of changing DELNOL, the design life of the asphalt pavement is always controlled by the fatigue cracking. When the allowable convergence accuracy is low (e.g., less than 0.01), the design life obtained by the analysis is significantly lower than that calculated by the default value of the program. The lower the allowable convergence accuracy, the less the actual number of iterations, and the calculation results are relatively rough. When DELNOL is higher than 0.01, the obtained design life tends to be stable, and it is of little significance to continue to improve DELNOL. Therefore, it is reasonable for KENLAYER program to set the default value of DELNOL to be 0.01.

In addition, Huang (1993, 2004) and Jiang et al. (2021, 2022) do not clearly indicate the upper limit of ITENOL, only the value of 15 is recommended. After many attempts, the author found that there is an upper limit on ITENOL, and the upper limit is 20. If ITENOL is set to a value exceeding 20, only a maximum of 20 iterations are allowed in the program calculation, and then the 20th calculation result is taken for subsequent calculations. Compared to the recommended value of 10 for the DOS version of the KENLAYER program (Huang 1993), the

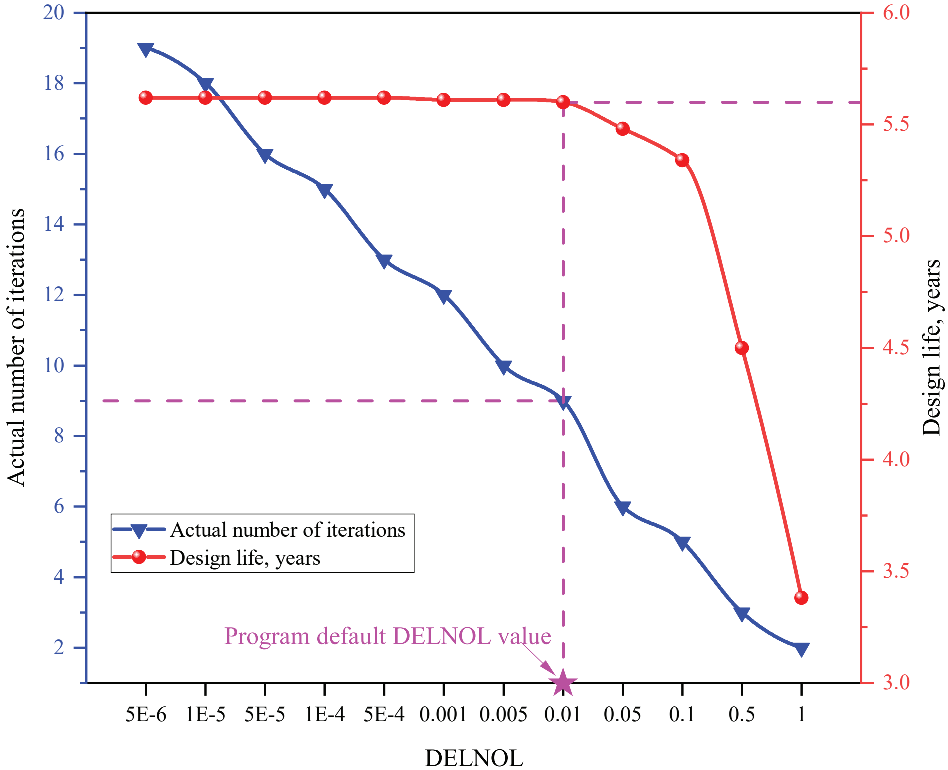

Figure 11. Relationship between RELAX and actual number of iterations and design life

recommended value of ITENOL has been adjusted to 15 in the WINDOWS version, but considering the great improvement of computer hardware condition, it is suggested to increase the recommended value of ITENOL to be 20 to avoid the occurrence of iteration problems as much as possible.

(3) Relaxation factor for nonlinear analysis RELAX

RELAX is a parameter commonly used in nonlinear iterative calculations to control the speed of convergence and improve the state of convergence. After introducing RELAX, the K–θ model should actually be expressed as:

$$E = E' + (K_1\theta^{K_2} - E')\beta, \qquad (1)$$

where E' is the elastic modulus obtained from the previous iteration; β is RELAX, if β is 1, the formula is the same as the formula shown in Figure 2.

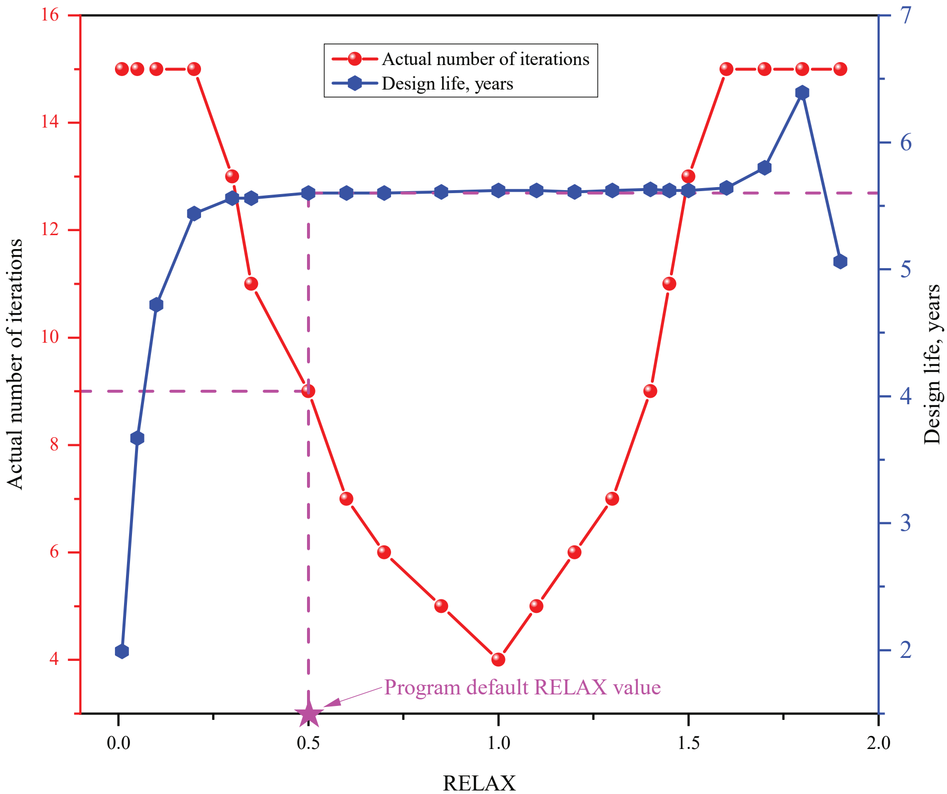

Figure 12. Relationship between RELAX and actual number of iterations and design life

On the basis of Section 2.2.1, it is necessary to only change RELAX, and let the other iteration-related parameters remain unchanged ($E = K_1$, ITENOL = 15, DELNOL = 0.01). Figure 12 shows the law of the actual number of iterations and the design life with the change of RELAX.

It can be seen in Figure 12 that when RELAX is very small, the actual number of iterations required is more, and there is a risk that ITENOL is reached but the convergence accuracy does not meet DELNOL. And this will lead to complete distortion of the calculation results. As RELAX increases to 1, the actual number of iterations gradually decreases, and the design life remains the same under the condition of satisfying DELNOL. When RELAX exceeds 1.0 and continues to increase, the actual number of iterations begins to increase again until it reaches ITENOL, which again causes the problem that DELNOL cannot be satisfied.

Sub-layer 1 is more affected by the load due to above other sub-layers and closer to the load. Sorting the elastic modulus of each RELAX of sub-layer 1 in the iterative process into Figure 13, it is easy to see that when RELAX is less than 1.0, the elastic modulus will be iterated in one

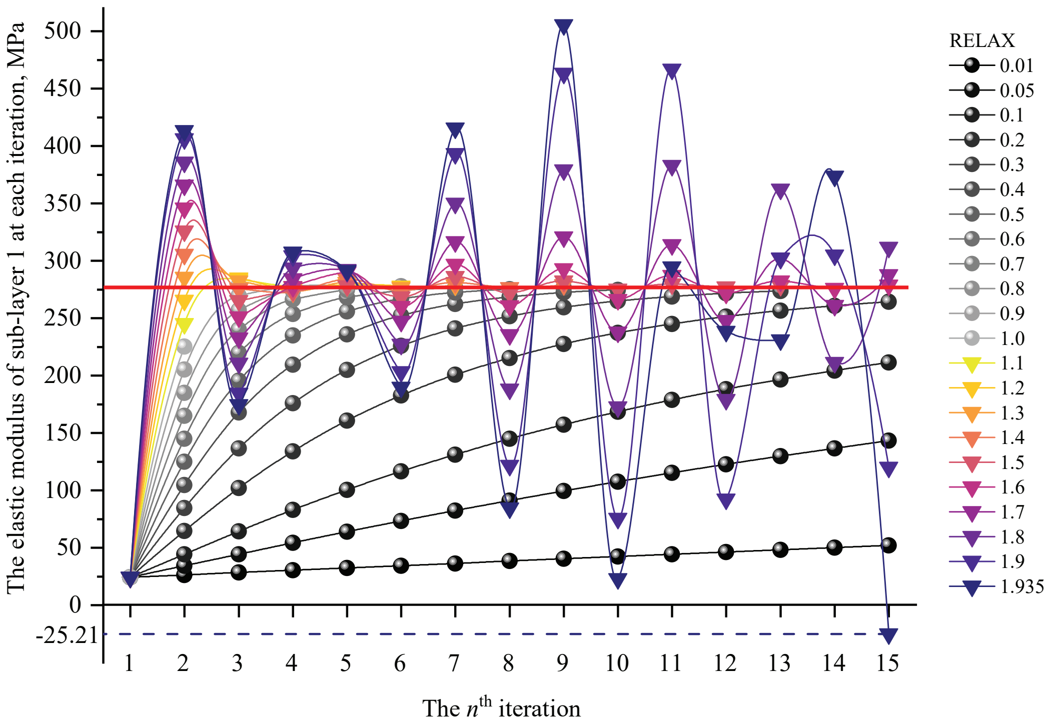

Figure 13. Iterative process of elastic modulus of sub-layer 1 corresponding to different RELAX

direction from low to high during the iteration process, and the value of elastic modulus will gradually approach the final iteration result from K_1. When RELAX is greater than 1.0, the elastic modulus approaches the final iteration result from both high and low directions at the same time. The larger the relaxation coefficient, the worse the convergence, the greater the difference in elastic modulus between the two iterations, and eventually let the convergence be lost. During this process the elastic modulus may even show negative values. If a negative value is used as the final calculation result reaches to ITENOL, the design life of the asphalt pavement structure in this case is changed to be controlled by permanent deformation.

Keeping increasing RELAX until the elastic modulus appears negative during the iteration process (the actual number of iterations less than 15 times), as shown in Figure 14, RELAX is set to 2.0 which causes the value of elastic modulus of layer 3 (Sub-layer 1) appearing negative, at this time the program begins to report error.

To sum up, when setting RELAX, it is not recommended to take a value greater than 1.0. Even though sometimes correct calculation results can be obtained, the convergence stability is not as good as setting RELAX between 0.0 and 1.0. Therefore, in general, it is reasonable for KENLAYER program to suggest that RELAX should be set to 0.5. If the actual number of iterations is too large, RELAX can be

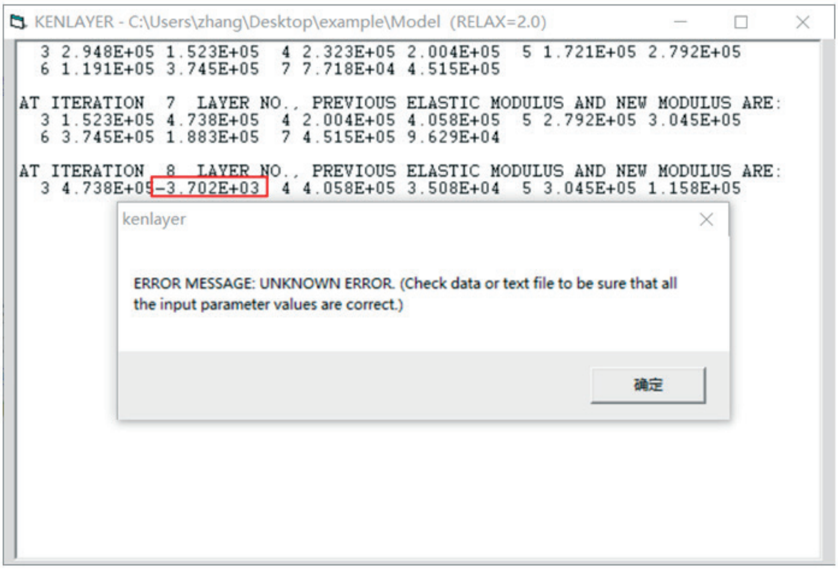

Figure 14. Program error

appropriately increased to speed up the convergence; if the convergence is not obvious during the iteration process, RELAX can be appropriately reduced to improve the convergence.

Conclusions and recommendations

This paper discusses systematically the influence of nonlinear analysis technology on damage analysis based on the elastic layered system theory with the help of KENLAYER computer program. The changes brought by the stress adjustment method and the iterative parameter selection to the damage analysis results are presented, the causes of damage analysis errors brought by both are analysed, the effects of improper selection of both on the dominant damage mode are clarified, and relevant suggestions for reliable damage analysis under nonlinear conditions are given, with the following specific conclusions.

1. The errors caused by the stress adjustment methods are mainly due to the fact that when the structural layer above the granular layer is very thin, the stress invariant θ in the granular layer is dominated by the loading stress and varies greatly in the depth direction. In turn, θ is directly related to the modulus, resulting in a large difference in the modulus in the depth direction of the granular layer. In this case, Methods 2 and 3 both treat the granular layer as a whole layer and use the same modulus, which is obviously unreasonable.
2. The error caused by improper selection of iterative parameters is mainly due to the fact that the actual number of iterations reaches ITENOL but the convergence accuracy of elastic modulus does not meet DELNOL, the program cannot automatically report an error and directly selects the result of the last iteration for subsequent calculations. In addition, this paper has found that the upper limit of ITENOL can be set to 20 times, if the calculation process is still up to 20 iterations, the user needs to manually check the convergence accuracy of the final iteration results, if it does not meet DELNOL, the relaxation factor RELAX should be increased appropriately to recalculate.
3. In this paper, the error caused by E, DELNOL, and the stress adjustment method, are all limited to the specific value of the design life of the pavement structure, and do not change the dominant damage mode of the asphalt pavement. When the final iterative elastic modulus has a negative value, the error caused by RELAX may change the dominant damage mode of the asphalt pavement.

It should be noted again that the discussions are mainly based on the representative program KENLAYER. And only two typical asphalt pavement damage types, fatigue cracking of asphalt surface layer and permanent deformation of subgrade, are considered. Hence, further field tests are needed to evaluate and validate more suitable nonlinear analysis input parameters for asphalt pavement structures with granular layers of different surface layer thicknesses.

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