A Study on Stability Control of Soft Subgrade Tarmac under Traffic Moving Loads

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Abstract **– In view of the low plasticity, low density and vibration response of soft roadbed, we propose a new method to stabilize soft subgrade by studying its deformation under moving traffic loads. First, we used the STX-200 two-way vibration apparatus to conduct a dynamic tri-axial test on a silty soil sample from the highway in Zhengzhou city, and observed: i) under a low frequency cyclic dynamic load, the amplitude of the soil's stress-strain curve experienced only minimal change, ii) when the cycle time was lengthened, the pore water pressure of the soil rose and the amplitude of the effective average compressive stress gradually increased, iii) thus the pore water pressure of the silty soil sample changed with cycle time. Then we analysed the liquefaction characteristics of the soft soil subgrade and considered the influence of: cyclic loading time, loading frequency, confining pressure, axial pressure and deviatory stress. Then: i) we built a 3-D dynamic mathematical model under traffic loading and determined the basic amplitude to estimate the frequency response threshold as a vehicle passes the road, ii) we calculated the soft roadbed space model, and iii) analysed the vibration amplitude, shear stress and relationship with liquefaction risk of the soft roadbed. The simulation results and conclusions are summarised in the last section of the paper.**

Keywords - Soft subgrade; dynamic tri-axial test; stability control; traffic moving load.

I. INTRODUCTION

With the rapid development of highways, the road transportation has become the main transportation method. Because the horizontal and vertical alignment demand of the highway is high, it is hard to avoid encountering bad foundation especially along the soft soil roadbed. This is common in China's coastal and central regions. Many of the soft roadbed soil is low liquid limit clay powder. It is a kind of powder soil. It has part of the powder soil characteristics, also with part of the cohesive soil properties. So its processes are duplicated. This kind of soil is similar to silt soil and flexible. But it is not sand and lack of resilience, with obvious shake vibration response and low strength. This kind of subgrade is often called soft subgrade.

The problem about soft subgrade engineering application has aroused widespread attention. In the current study, there are major problems of compaction difficulties and low subgrade strength in the roadbed. It is the major problem of powder soil constructing subgrade that slope is easy to scour. Four kinds of diseases, crack, transverse crack, subsidence, cracked longitudinal crack, are the main disease form of highway pavement in soft soil area [1]. Besides, capillary water of soft soil rises high. In seasonal frozen regions it is more likely to make an embankment moisture accumulation. It is easy to cause serious frost heave and pumping [2， 3]. In order to overcome the bad performance of powder soil, many scholars at home and abroad do a lot of research work of powder soil. There are some findings research the soft subgrade response under traffic moving loads including: the influence of uneven settlement on pavement structure through the calculation of highway embankment settlement [4]; the subgrade stability and deformation of slope soft foundation [5]; damage problem of highway asphalt pavement structure overloading and transfinite vehicles cause[6],etc. In the roadbed compaction technology, through roadbed fill pressure test, compared with ordinary roller, using impact roller compaction can effectively improve the mechanical speed, product thickness and pressure entities, reduce the number of compaction, and in a certain extent soft demand for water content of subgrade soil compaction [7， 8]. In order to improve the filling technology of soft soil roadbed and the stability of the silt, such research is not confined to the construction technology, but should completely figure out physical mechanical properties and road performance of silt. Starting from the preliminary classification of soft soil, focus on strength, deformation characteristics and compaction characteristics of soft soil, establish road classification index and classification criteria of soft soil, and systematically review the domestic research in these aspects [9]. Through the study of soft soil properties, some researchers point out the deficiency of the routine laboratory test in soft soil characteristics [10， 11]. On that basis, the deformation prediction methods are put out after soft soil foundation liquefaction [12]. These research results are helpful to improve subgrade filling technology. But under traffic load, the research of the development deformation of roadbed uneven settlement over time is rare [13].

Generally after higher highway is built and opened to traffic, in order to ensure the use quality of pavement, should pay attention to the treatment of special section of subgrade. And deformation of roadbed is the important basis to decide whether the sub grade to deal with [14]. For soft subgrade, since it has the characteristics of low plasticity and low intensity, under the mobile traffic moving loads, non-uniform deformation soft subgrade causes results in the crack of the embankment [15]. Excessive deformation and increased stress of the road affect driving comfort and lead to the amount of highway maintenance increase [16]. Excessive uneven settlement will lead to a drop in the road elevation and affect the normal use [17]. These phenomena have a strong impact on stability and security of the car at high speed [18, 19]. It is difficult to achieve its service purposes, “safe, comfortable, high speed”. Therefore, deformation and stability research of the soft subgrade under traffic moving load becomes an important subject in the process of highway construction [20, 21, 22]. It is of important guiding significance for high grade highway construction under the condition of soft subgrade.

II. LABORATORY TEST

A. *Soil Samples*

The topsoil of the Zhengbian logistics channel (located in Zhengzhou, China) is typically the cultivated portion of the land (silt and silty sand) and exists in a dense state. The soil layer that lies below the surface consists of silty clay, silt, and sand. Additionally, the subgrade soil primarily consists of the sand loam that is clamping the silty sand as well as contains multi-layer soft soil, thin lens, and small amounts of recently deposited soil. Part of the saturated soil probably liquefies, resulting in poor engineering properties. The underground water level resides deep in the land, at approximately 1.50 ~ 3.50 m, and is primarily buried in the quaternary Holocene and the fourth Pleistocene series powder in the soil and sand, which belongs to the weak, medium permeable layer. The basic physical indices of the soil are presented in Tab.1.

TABLE.1 GEOTECHNICAL PARAMETERS OF NATURAL SUBGRADE

Layer	Depth (m)	Thickness (m)	Soil type	Groundwater (m)	Clay content (%)	Standard penetration depth ds points	Liquefaction resistance coefficient
1	0.00～5.90	5.90	Silt	2.80	10.80	3.35	0.79
2	5.90～8.00	2.10	Silt	2.80	12.90	7.35	0.61
3	8.00～13.30	5.30	Sand	2.40	3.00	15.15	3.05
4	13.30～28.60	15.30	Sand	1.60	3.00	17.15	5.99

B. *Test Instruments*

The primary instrument used in this test was the STX - 200, a two-way dynamic triaxial apparatus, produced in the United States by GCTS Testing Systems. A direct, digital servomechanism controls the axial load, the confining pressure, and the pore water pressure for all the gay and heterosexual consolidations of the conventional static triaxial test of saturated soil (UU, CU and CD), the advanced static triaxial test (the stress path and strain path), the dynamic triaxial test (stress path, the dynamic shear strength and deformation, residual modulus, the liquefaction potential analysis, shear modulus, damping ratio, soft modulus, etc.). The system can also conduct a two-way triaxial vibration (dynamic bidirectional loading) test. The bidirectional dynamic triaxial apparatus is controlled by the hydraulic station, the general purpose digital signal conditioning control unit, the load and triaxial pressure chamber, the pressure/volume controller, and the CATS software. The test’s hydraulic station is powered by the axial, the confining pressure, and the back pressure actuators and also has two working modes: low pressure and high pressure. The general purpose digital signal conditioning control unit contains a built-in 850 MHZ microprocessor with 64 MB of RAM and 64/128 MB of hard drive storage. The built-in CATS software is a set of complete and self-contained modules, including the function generator, the data acquisition, and the digital input/output unit and is connected to the computer to complete the data acquisition and control functions. The test adopts the SCON - 1500 microprocessor.

This experiment uses a CATS software interface, incorporating a 32-bit Windows computer aided test software (advanced edition and standard edition), that is currently the most advanced senior test software on the market. Based upon the style size, the software allows users to directly test the calculation parameter programming with the parameters of interest (such as stress and strain), simplifying both the instrument and test operations. These parameters are calculated in real time and can be used for real-time display, graphics, or control. Using the calculated test parameters, the long and complicated pre-computation process of designing the test program can be directly eliminated. The test module is comprised of: saturation, consolidation, static load (UU, CU, CD, and stress path), dynamic loading, and the general module (a high load module, users can custom load the waveform).

C. Test program

According to the domestic and foreign information on subgrade dynamic loads, the traffic load is a low frequency load (generally less than 5Hz). In order to retain the undisturbed soil's structure, the test incorporates a moisture content of 20% and a dry, heavy control of 15.0 KN/m2. Under three different compaction degrees (93%, 95%, and 98%), the soil damage threshold was observed for a dynamic load of 100-500 kpa. Experiment schemes of tri-axial loading environment under different conditions are shown as Tab.2:

TABLE 2 EXPERIMENT SCHEMES OF TRI-AXIAL LOADING ENVIRONMENT UNDER DIFFERENT CONDITIONS.

Compaction degree	Confining pressure	Axial pressure	Partial stress	Loading frequency
93%	50	75	25	2.5
	100	150	50	5
95%	50	75	25	2.5
	100	150	50	5
98%	50	75	25	2.5
	100	150	50	5

D. Test procedure

The test soil was taken from the Zhengbian logistics channel field. Three parts of the soil sample were randomly extracted, and in order to determine the soil's moisture content, the "dry method" of "test procedures" SL237-003-1999 was used. The moisture content of every part from the two groups was measured, and the final average measured moisture content was 20%. Because the soil was silty, viscous, small, and unable to be moulded, the "sample loading on board the compaction load" test mode was used. The calculated maximum dry density of the soil was 1.7 g/cm3. Next, without changing the soil moisture content, the sample was tested after striking and loading it according to the different compaction degrees (93%, 95%, 98%). The test procedure is as follows:

(1) sample loading: According to the test's required moisture content, calculate the soil number and use the electronic day to equally take those 5 times. Point 5 layer to strike and load the sample. Before loading the sample, check the seal of the rubber membrane. For paper tests, use cylinder specimens of the diameter 50 and the height 50 . Samples are prepared according to a moisture content of 20.0% and an initial dry density of about 1.7 . After completing the broadly graded soil, seal it airtight, and let it stand for at least 24 hours in order to obtain fully uniform water.

(2)Saturated: First use the "vacuum saturation method" and open the confining pressure action so that 50 confining pressure is placed on the sample. Furthermore, deviator stress is set to 0. Then, suction the sample in order to eliminate any air in the sample. When using the "vacuum saturation method" for a certain time, the effect is not obvious. At this time, open the back pressure action so that 30 back pressure is added to the sample. Using water, draw out any bubbles within the sample. When B is greater than 98%, saturation is considered to be complete (that is $B=\Delta u/\Delta\sigma 3\geq 98\%$).

(3) Consolidation: After completing the saturation, concrete the sample with the method "Range to consolidation." The confining pressure is set to 100 KPa, the axial pressure is set to 150 , and the back pressure is closed. Observe whether the axial displacement of the specimen within five minutes time is greater than 0.005mm. Because the instrument's measuring accuracy is only accurate to 0.1mm, directly observe whether the axial displacement of the specimen is greater than 0.1 mm in 100 minutes time. If it is not, the consolidation process is complete.

(4) Load: After the completed consolidation, gradually load the sample with the vibration frequency set to 2.5 Hz or 5 Hz and a vibration time set for 500 times. In the loading process, the CATS software will automatically record the loading data. Finally, the required data is derived.

III. THREE-DIMENSIONAL DYNAMIC MODEL

The traffic load is a kind of mobile fatigue load. It is totally different from the characteristics of dynamic load, such as earthquake. The traffic load is not a constant value. It will change as the change of vehicle size and speed. So the traffic load simulation always is a difficult problem.

For fixed position of soft subgrade, transient load effect time of traffic load is very short. But along the length wise direction of subgrade, the effect of moving load is very long. This is because the subgrade exists propagation and attenuation of stress wave. Considering the dynamic property of traffic load, this paper described it with variable amplitude loading realistically. And through loading the traffic load on road surface, the form of time step move. Use Ansys for 3 d dynamic calculation. On the basis of dynamic analysis, simulate force and deformation characteristics of saturated silt under long-term traffic load, and carry them on the detailed analysis.

A. Traffic Load Feature

(1) Dynamic Load Pressure Calculation: Once car is installed, power system's maximum power is fixed. The cost and difficulty of reform are large. The overload vehicles reduce traffic resistance in order to improve the efficiency. Use high-strength tires and thicken spring. This makes truck tire pressure generally greater than 0.7 Mpa. By the principle of vehicle structure, with the increase of axle load, the grounding radius and area also will increase, but the tire spacing, the tire load centre distance, is not possible to vary with the change of the degree of overload. Design specification of asphalt pavement in our country adopts the double wheel and double circular load. Circle centre distance of standard load is equal to three times pressure is 0.7 MPa which can be shown asFig.1.

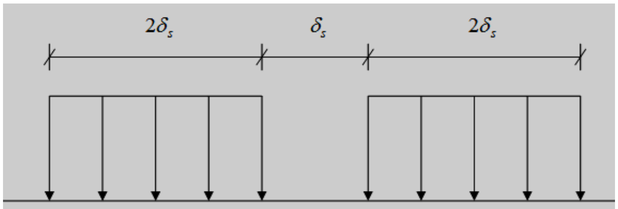

Fig.1 The standard load calculation chart

The determination of vehicle load refers to "highway bridge design specification". Use steam level -20 load of 300 kN weight. Gravity of front axle is 60 kN and gravity of rear axle is 240 kN. Consider affection of the power amplification in the calculation. Increase each axle load and simplify load as two impacts to load on the floor. The peak value of axial load in the experiment is 250 kN through four wheels (two pairs) for loading. When calculating, quantize double circular uniformly distributed load to two square uniformly distributed load of equal strength, with load spacing unchanged, wheel gap center as the origin and considering the double load superposition. This study simulates the process speed of typical large truck 90 km/h. wheel pressure of all levels of axle load is according to the formula (1) to determine.

$$p_i / p_s = (P_i / P_s)^{0.65} \tag{1}$$

Formula: p_s - Standard wheel pressure, p_s=0.7MPa ;

P_s - standard axle load, P_s=100KN ;

p_i - wheel pressure of calculation , MPa ;

P_i - axle-load of calculation , KN .

Through calculation, related axial load calculation parameters are shown in Table 3.

TABLE.3 AXIAL LOAD CALCULATIONS

axle load P(KN)	100	130	160	190	220	250
wheel load (KN)	25	32.5	40	47.5	55	62.5
wheel pressure P(MPa)	0.70	0.83	0.95	1.06	1.17	1.27
equivalent rectangle long (cm)	22.74	23.85	24.72	25.52	26.11	26.73
equivalent rectangle width (cm)	15.66	16.43	17.03	17.57	17.98	18.41

The surface is the main load bearing part of pavement structure. It loads the most dynamic additional stress caused by vehicle load. This research mainly analyses the influence of the surface properties to layered foundation mechanics response and do interface damage analysis.

(2) Select pavement structure form: This research adopts the common layer structure, determined as the pavement structure form can be shown as Tab.4, the grass-roots level for cement stabilized gravel, sub base for cement stabilized soil, under for saturated silt embankment, bed for rock subgrade.

TABLE 4. SOFT PAVEMENT STRUCTURE FORM AND CALCULATION PARAMETERS

Name	Location	Thickness (m)	Modulus of elasticity (Pa)	Poisson ratio μ	Density Kg/m^3
Asphalt surface	First floor	0.1	1.5E+09	0.25	2350
Cement stabilized crushed stone base	Second floor	0.18	1.6E+09	0.25	2400
cement stabilized soil	Third floor	0.32	7E+08	0.25	2350
saturated Silty Soil	soil roadbed	2	1E+08	0.34	2300
foundation bed	Rock mass subgrade	5	1E+09	0.3	2400

B. Numerical calculation model

According to the structure of road, carry on similar model, using connection of common Gauss point between the layers. The finite element calculation result are shown as Fig.2-3:

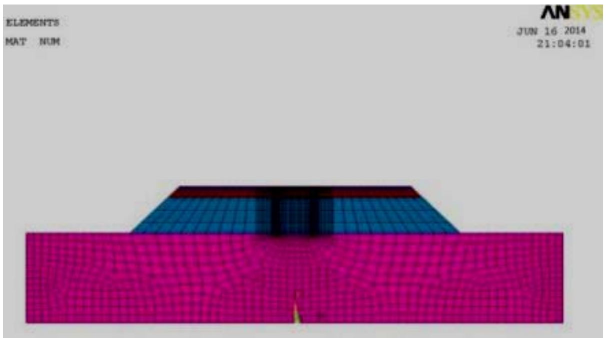

Fig.2 The cross-section diagram of finite element model

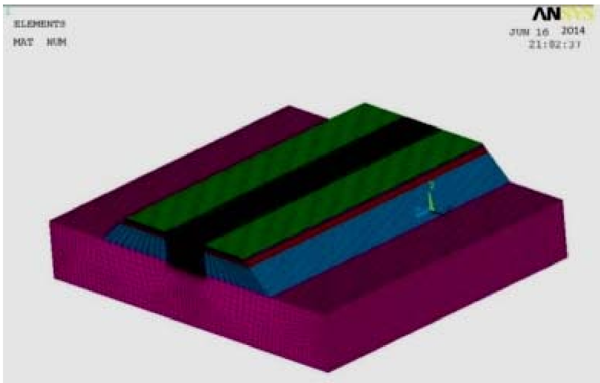

Fig.3 The ensemble diagram of finite element model

Boundary conditions are assumed: there is no Y direction displacement on the bottom; no X direction displacement on both before and after sides, no displacement Z direction on both left and right sides. This study chooses solid45 unit used in three-dimensional entity structure model. The unit consists of eight nodes. Each node has three freedom of x, y, z directions. The unit has the characteristics of plastic, creep, expansion, the stress intensification, large deformation and large strain.

C. Finite element model

For the dynamic numerical analysis of engineering structure problem, the grid division of finite element model should be able to simulate the wave shape to obtain more accurate results. In the physical sense, the continuum will cause two kinds of adverse effects after discretization. A kind is called "low-pass effect" and another called "dispersion effect". They will make the wave propagation properties change. However, the theory and practice prove that, when the dividing grid size is enough little, error of using the finite element discrete model instead of the continuous medium model to solve is usually negligible. Among wave propagation problems of 2 d and 3 d discrete model, in addition to the dispersion, cut-off frequency of one dimensional discrete model; it will also introduce new problems with the increase of dimension. Therefore, when analyzing transient wave propagation problems, unit grid size should be small enough. By studying comparatively, two following conclusions can be summarized: grid range R of finite element is best greater than 1.5; grid length L of the unit should be less than. In the concrete structure, shear wave velocity is about 2400 m/s. wave length of 100Hz waves is 24 m. As modelling, the cell size of beam, plate, column should be controlled within 3 m, to meet the requirements of unit size segmentation criteria. Concrete structure damping ratio is 0.02. Damping coefficient should be according to the typical vibration frequency, f = 5 Hz and f = 80 Hz. In special soft soil, the shear wave velocity can be as low as 100 m/s. For 100 Hz waves, its wavelength is 1 m. As modelling, the soil element size should be controlled between 0.0833 ~ 0.125 m. And then calculate the complete waveform series. Of course, Actual calculation may be not support such a subdivision mesh, and computational cost is too big, especially for the power problem. In fact, the requirement can be loosen, and the fundamental amplitude of vibration also can meet the basic requirements.

IV. STABILITY CONTROL ANALYSIS

A. Subgrade Deformation Analysis

The main factors of liquefaction potential are stress gradient, hence there uses stress to judge. Driving on a road surface, analysing the degree of stress concentration graph of longitudinal impact range is about 3.5 mand transverse impact range is about 3.2 m, which can be expressed as Fig.4-5.

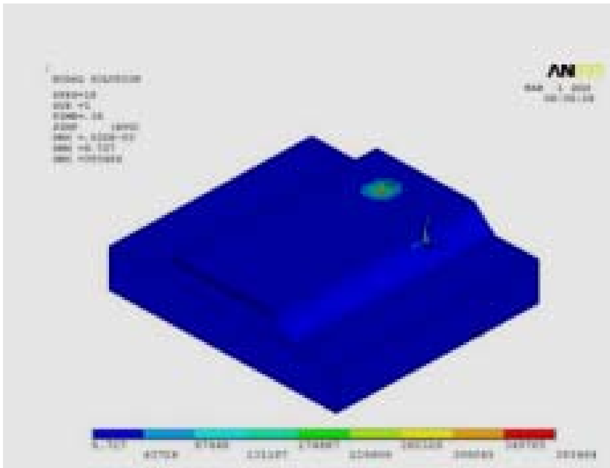
Fig. 6 The degree of stress concentration in step 18

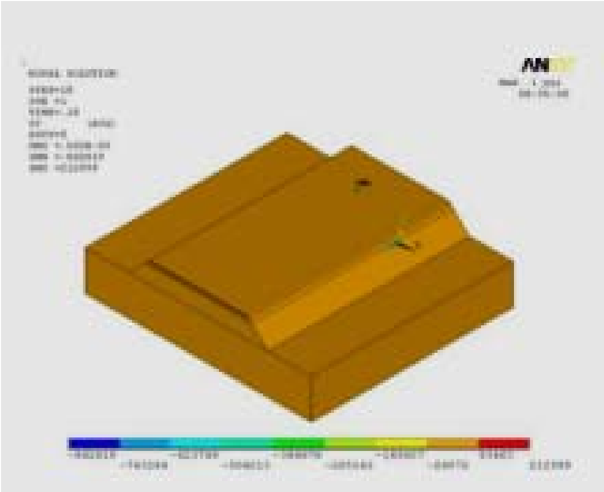

Fig. 5. The vertical stress in step 18

This has vital effect in driving direction and further study of subgrade dynamic stress characteristic must start with dynamics. Considering with stack effect of the axial load, maximum vertical displacement in step 18is 0.564 mm, as shown in Fig.6.

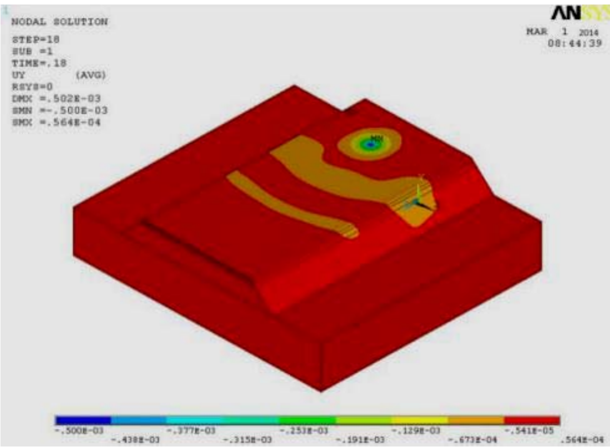

Fig.6 The total vertical displacement in step 18

As the increase of the depth of road, in the road surface below the 4.75 mm to 110 mm, the vertical shear strain is bigger than the transverse tensile strain. On the contrary, in the soft roadbed soil, tire load caused that longitudinal and transverse tensile strain is greater than the vertical shear strain. In the most dynamic stress wave, dynamic shear stress is used to determine liquefaction probability. Therefore, this study argues that the corresponding soft subgrade dynamic shear strain amplitude is quite important. It is a main role at liquefaction process of saturated silt.

B. Stability Control Analysis

Under two Wheels loading, there is pavement counter-force which is shown as Fig.7.

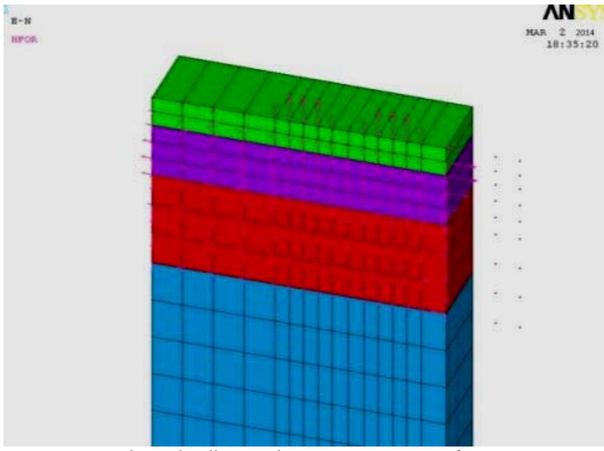

Fig.7 The diagram in pavement counter-force

Soft subgrade displacement amplitude is shown as deflection of subgrade. it is the vertical deformation of the road surface under vehicle load. And it is one of the most intuitive and simple index that reflects the overall carrying capacity and use condition of road surface. From the side reflects, it is also the important parameters of subgrade vertical dynamic displacement amplitude. It is formed by the deformation of each structural layer of the road and roadbed, so the deformation reflects the bearing properties of the pavement layer and soil base to a certain extent. Roadbed displacement amplitude also reflects the level of motivation of soil. Thus it can be used as liquefaction risk related indicators in a sense. Based on the equivalent strain, dynamic shear strain nephogram, make the soft subgrade equivalent strain under traffic moving load which can be shown as Fig.8.From the nephogram, under the traffic moving load in a certain area, the road is under compressive stress, and the lateral wheel load is under tensile stress. Combined with the reality of transformation between traffic lanes on roads, there will have repeatedly moving loads of compressive stress and tensile stress. The pore pressure of saturated silt roadbed is accumulation.it is the reason that the road has many local sag.

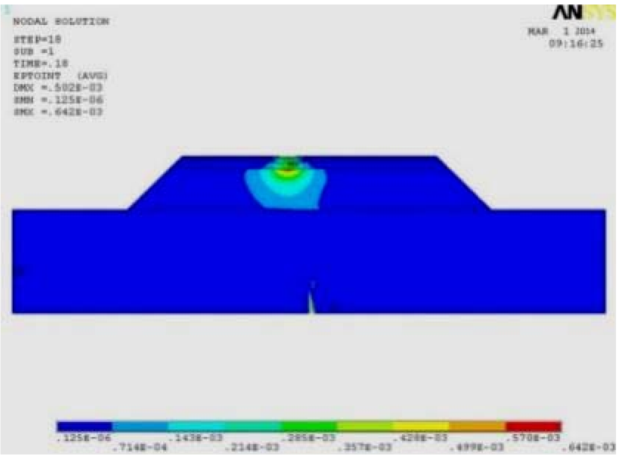

Fig.8 The equivalent strain nephogram in soft pavement

Under the effect of vehicle repeatedly, there is dynamic shear stress that has drastic effect of roadbed. It encourages the soil particles and influence pore water pressure. Thus, pore water pressure is improved to subgrade potential vibrating liquefaction and influence the safety performance of the road.

B1. Dynamic Response Analysis

Extract and sort out of the dynamic time-procedure of the fixed point in the whole process of driving, as shown in Fig.9-12 Under larger speed (in this paper it is 90 km/h), the inertia force from external force may be larger than which under low speed. When loading fast, the acceleration of dynamic system is increase. This leads to a short dynamic pulse rise time, and the void water pressure dissipates and increases. Thus, vehicle load of fast car is bigger than slow car, and it will produce more exciting force, at the same time it may cause a higher risk of liquefaction.

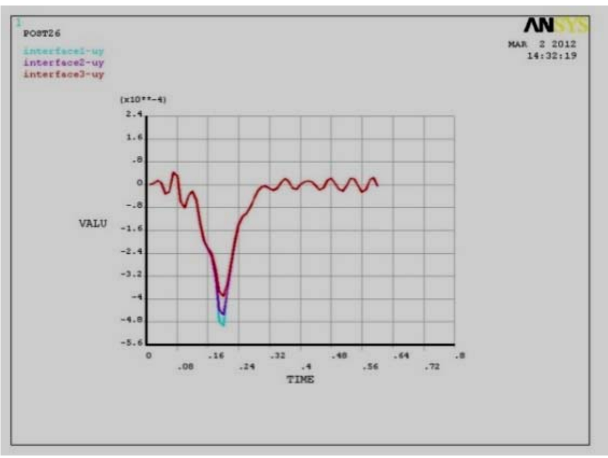

Fig.9 The vertical displacement time-procedure

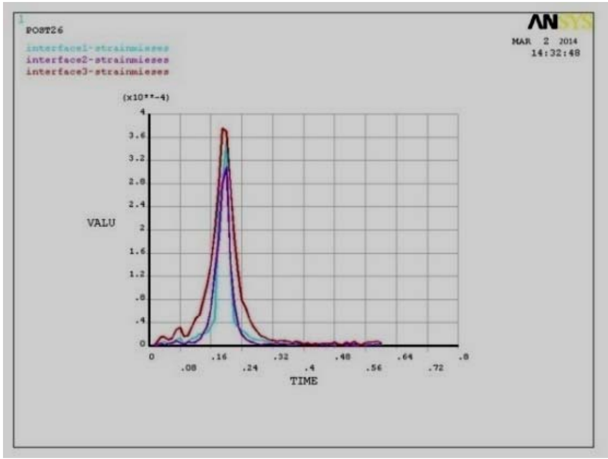

Fig.10 The equivalent stress time-procedure

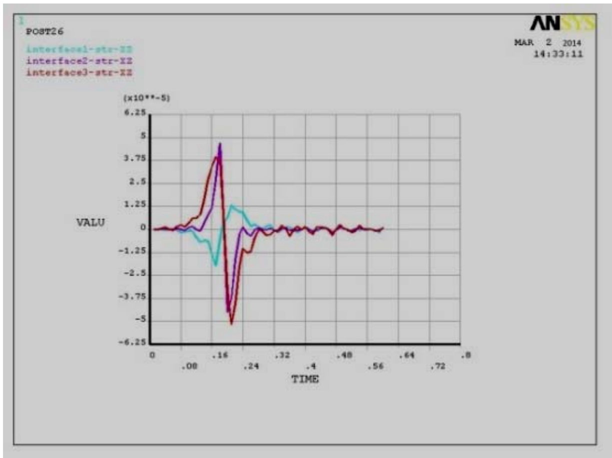

Fig.11 The shearing strength time-procedure.

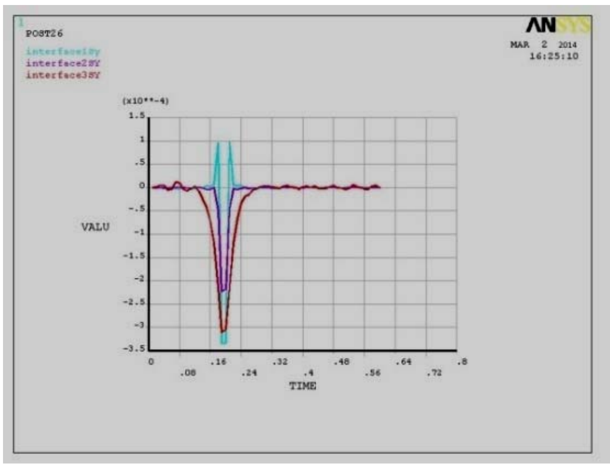

Fig.12 The vertical stress time-procedure

B2. The Analysis of Deformation and Instability

In order to master the deformation and instability behaviour of subgrade, the following section combined with the analysis of driving dynamic response, from the angle of dynamic displacement and dynamic strain, this paper further elaborates the roadbed liquefaction risk, as shown in the figures. Under typical car load (250 kN) at a certain speed (90 km/h), calculate the roadbed response caused by the moving load. At the same time, analyze the saturated soil compressive strain state are analyzed in detail.

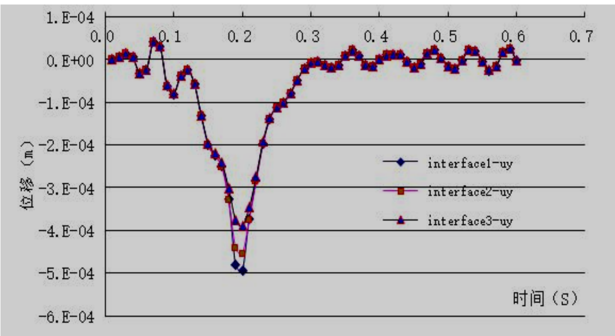

Fig.13 The submerge time-procedure

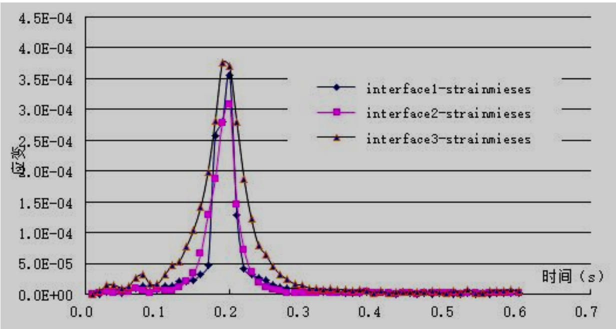

Fig.14 The equivalent strain time-procedure

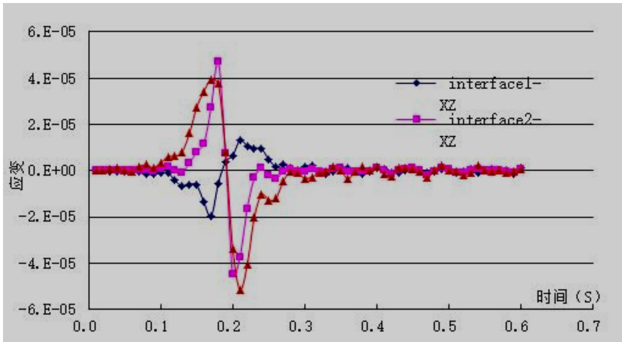

Fig.15 The strain time-procedure

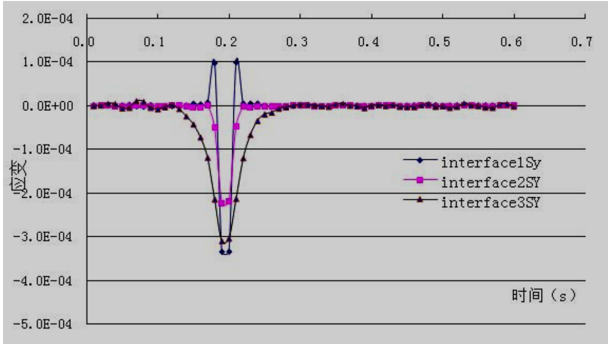

Fig.16 The vertical strain time-procedure

As shown in Fig.13-16, subgrade settlement deformation is concerned with the top of and the number of the compressive strain. Use the appropriate method to calculate the allowed repeat number of compressive strain load. In order to intuitive understanding, extract the vertical compressive strain. In a specific speed (90 km/h) and under the typical load (250 kN), roadbed compressive strain reach 335με in the first layer. It is one of the high quantities. And then plus higher fatigue cycle times. There has higher risk of deformation accumulation trend and vibration liquefaction.

V. CONCLUSION

In this paper we adopted the dynamic finite element method to simulate the dynamic effects of soft roadbed under typical conditions. We obtained simulation results for: i) the relationship between additional dynamic stresses and its liquefaction resistance, ii) relationship between additional dynamic stress and original effective stress of roadbed, iii) the assessment of liquefaction risk, and iv) the effect of the major factors for soft roadbed stability. The main conclusions are as follows:

(1) Under traffic moving loads, vibration amplitude of soft roadbed occurs below the centre of contact surface between the tyre and the road surface. When the axle load level is large, theoretical deflection values of road surface is much larger than road surface deflection values under standard axle loads, and ground vibration amplitude is greater than the static load effect.

(2) Under repeated vehicle moving loads, the vertical displacement of roadbed changed repeatedly. Thus, induced effect among the roadbed soil particles directly led to the increase of pore water pressure. This is the root cause of roadbed deformation.

(3) Because tensile stress along the horizontal distribution below the soft ground is negative, but grassroots tensile stress along the horizontal direction distribution is positive, descripting surface layer appeared bending and compressive deformation under repeated automobile loading, the layers below grassroots bend and undergo tensile deformation. The movement shearing

action is very strong in the bottom of the roadbed, once the soil is low plasticity and low density soft soil, more likely to cause damage to the roadbed soil liquefaction.

(4) Dynamical processes have superimposed effect, this paper used dynamic calculation to compensate for the shortage of the static calculation and make the result more scientific.

(5) Improving the quality of construction would mainly improve the density of roadbed soil, and we recommend further strengthening of pavement structure, reducing irregularity and the impact action of vehicle loads, and improve the relationship between additional dynamic stress and original effective stress. In the case of integrated measures, we need to fundamentally improve long-term settlement and soil liquefaction unstable phenomenon.

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