CHEMICAL ENGINEERING TRANSACTIONS
VOL. 51, 2016
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Tichun Wang, Hongyang Zhang, Lei Tian

ISBN 978-88-95608-43-3; **ISSN** 2283-9216
DOI: 10.3303/CET1651173

Study on Rheological Properties of Mountains Area Coarse--Grained Soil Embankment and Settlement Prediction Method

Ping Yang

Department of Civil Engineering, Hunan Technical College of Engineering, Changsha, China
yangpinggaga@126.com

Coarse-grained soil can used as high filling embankment in mountainous area, but rheological deformation of coarse-grained soil continue long time, which may cause the transfinite of post-construction settlement under long-term load. Coarse-grained soil engineering properties are greatly influenced by particle size composition, triaxial test for coarse-grained soil stress-strain relationship, result show that: stress levels and confining pressure effect rheological properties of coarse-grained soil, coarse-grained soil presents nonlinear viscoplastic deformation characteristics. Rheological calculating formulas of coarse-grained soil embankment are established based on Merchant model. Result shows that the total settlement which calculated by the formulas is more conservative than standard method.

1. Introduction

Embankment as the pavement structure bearing is designed to undertake vehicle load, the stability and deformation of it has direct influence towards the service life of the road. Research has shown that the breakdown of pavement structure is usually caused by deformation of embankment (Deng et al., 2004; Liu et al., 2006; Yang et al., 2016), Controlling the long-term deformation is crucial to freeway service quality. When the expressway is built in the mountain district of west Hunan province, restrained by landform, one of the characteristics of highway construction is fill root out the road over the high embankment, coarse-grained soil is a quite common highway embankment filling. Coarse-grained soil is a relative concept to fine-grained soils, mainly refers to soil composed of the coarse particle (e.g. sand, gravel soil, sandy pebble). Test method of soils for highway engineering (JTGE40-2007） defined coarse-grained soil as the total particle mass percentage of particle size d>60mm is no more than 15%, which mass percentage of particle size d>0.075mm is more than 50%.

A number of researchers have studied engineering characteristics through experiment at home and aboard, Fu(2014) has used a modified DSA to explore effects of gap and specimen size on shear strength, and proved to have significantly influences on shear resistance of coarse-grained soil. Cheng(1999) and Zhang(2004) have analyzed the influence of coarse aggregate percentage and dry density to the shear strength. Li(2002) mainly studied the shear strength influence factors of riverbed sandy pebble and blasted crushed stone and the relative variation law. Bagherzadeh(2009) studied the influence of particle size on shear strength of coarse - grained soils through experimental tests and DEM method, results show that the modification of sample gradation has a significant influence on the mechanical properties of coarse-grained soils. Fargnoli(2013) focused the settlement prediction in coarse-grained soils with the case-history of the new Milan underground line 5, a translated Gaussian cumulative curve was introduced to match the evolution of settlements. Liu(2008) studied the shear behaviour of dam coarse aggregates using a large-scale triaxial shear apparatus under different dam height, confining pressure and stress path, results indicated that peak deviator stresses increase along with confining pressures, whereas the peak principal stress ratios decrease as confining pressures increase. When coarse-grained soil is treated as freeway embankment, geogrid and piles are used extensively to reinforce the stability of embankment. Chen (2014) and Nie(2015)Specialized studied the shear behaviour of geogrid-reinforced coarse - grained soil and pile-soil interface respectively.

It is generally acknowledged that settlement of coarse - grained soil embankment is mostly done during construction stage due to high porosity and permeability. But expressway in mountainous area can still have noticeable post-construction settlement because of high filling embankment, it is caused by squeezing among particles and the slow development of rheological deformation which usually takes dozens of years to reach stability. The study on rheological deformation are rarely conducted, especially the long-term creep deformation. Until now, there are still no simple and effective calculation methods to obtain the consolidation settlement and creep settlement (Zhu, 2015). Aimed at deformation of high filling embankment in mountainous area, based on coarse - grained soil triaxial test, this work carried out a research of the rheological properties of the coarse - grained soil, and on that basis explored the granular soil embankment settlement prediction method with a typical project case.

2. Engineering properties of coarse - grained soil

Particles of coarse-grained soil are variable in size, scattered in composition, and complex engineering properties. Although coarse-grained soil have diverse mineral composition, weathering degree and gradation composition, but still they have something in common, they all have large density with high strength, carrying capacity, and small deformation under load (Bell, 1992).
Coarse-grained soil is made up of coarse - and fine aggregate, when coarse aggregate is less than 30%, the coarse ones are wrapped by fine ones, the engineering properties are basically decided by properties of fine aggregate. If fine aggregate is made up of cohesive soil, then the coarse-grained soil has the properties of sandy soil. If the percentage of coarse - aggregate is between 30% and 70%, Coarse and fine aggregate fill each other, both properties are presented at the same time, and with the percentage increasing, so is shearing strength，dry density and permeability coefficient. If the percentage of coarse - aggregate is more than 70%, fine aggregate can't fill the void among coarse aggregate, exhibiting the character of aerial material (Maksimovi, 1989), the engineering properties of coarse-grained soil depends on coarse - aggregate.
From the analysis above, as the percentage of coarse aggregate varies, the engineering properties vary widely. Especially when the percentage of the coarse aggregates is more than 70%, exhibits the character of aerial material with fast drainage consolidation property. Shearing rate has little effect on consolidation rate of coarse - grained soil, which is a feature not found in fine grained soil. Fast drainage consolidation property is the main advantage of coarse - grained soil as the embankment filling. The combination is not close enough among particles, therefore it's possible for the particle to redistribute or even break under a certain stress state, that is rheological deformation, thus when coarse - grained soil embankment is adopted, it's quite necessary to control the settlement, therefore laboratory experiment is required to study its rheological properties.

3. Rheological characteristic test of coarse-grained soil

3.1 Experimental contents

The available apparatus of coarse-grained soil laboratory rheological test including: one is test apparatus to exert shear strength (e.g. direct shear apparatus, torsion shear apparatus); another is apparatus to utilize uniaxial compression or uniaxial tensile test(e.g. compression creep apparatus, tensile creep apparatus, Bending creep apparatus). triaxial apparatus can control drainage condition, measure pore pressure and restrict lateral deformation of sample. Through triaxial test we can get stress-strain characteristic of coarse - grained soil, and attain the influence of confining pressure, stress level and compaction degree.
Red sandstone is wide spread in Hunan province. Red sandstone embankment was brought to Part of Shaohuai highway, specimen of coarse-grained soil embankment were collected along the field test site, gradation of the sample are as shown in table 1..

Table 1: Gradation of coarse - grained soil specimen

Gradation particle size /mm	Grain percentage (%)								
	300~150	150~80	80~60	60~40	40~20	20~10	10~5	5~0.1	<0.1
1# specimen	100	93.8	84.4	75.6	64.9	40.5	27.4	19.4	4.1
2# specimen	100	92.4	83.1	72.3	59.8	39.6	27.1	15.7	5.2

3.2 Experimental scheme

This experiment considered the influence of three aspects: confining pressure, stress level and compaction degree. Tests were conduct with confining pressure 100/200/300 respectively, stress level 0.2/0.4/0.6/0.8/1.0, and compaction degree 90/93%, the specific test scheme design is as shown in table 2.

Table 2: Test designs table

Group number	Confining pressure	Stress level	Compaction degree
A1	100	0.2/0.4/0.6/0.8/1.0	
A2	200	0.2/0.4/0.6/0.8/1.0	90
A3	300	0.2/0.4/0.6/0.8/1.0	
B1	100	0.2/0.4/0.6/0.8/1.0	
B2	200	0.2/0.4/0.6/0.8/1.0	93
B3	300	0.2/0.4/0.6/0.8/1.0	

3.3 Experimental scheme

After finishing the granular soil triaxial rheological tests according to the test scheme, figure 1 shows under the compaction degree 90% and 93% respectively, the coarse - grained soil stress-strain curve under different confining pressure, according to our analysis: on the starting section of the curves, stress is growing rapidly with the development of the strain course, strain can reach a high value with only a smaller stress. Stress reaches peak then gradually decrease with the increase in strain, exhibit strain soften characteristics. The same soil sample, with the confining pressure higher, the peak of stress-strain curve becomes higher, and so are failure strain values. As confining pressure σ=100kPa, failure strain<5%; As confining pressure σ=200kPa, failure strain is 4-8% approximately; As confining pressure σ=200kPa, failure strain is 4-8% approximately; As confining pressure σ=30kPa, failure strain increases to 6-10% approximately. From the analysis above, increase the lateral pressure can enhance the breaking strength of coarse - grained soil. With a lower confining pressure, strain softening features are becoming more obvious.

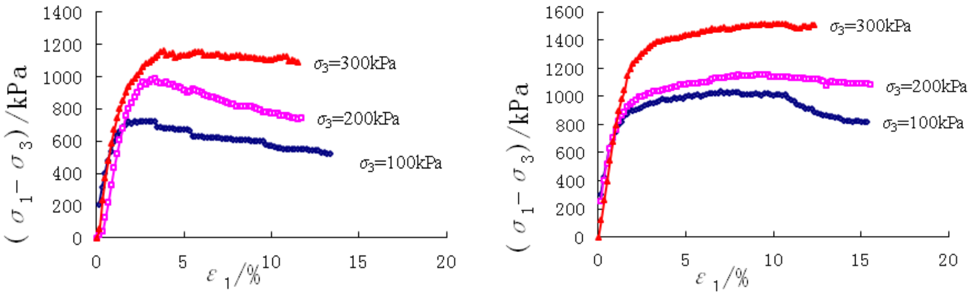

Figure 1: stress-strain curve under compaction degree 90 %(Group A) and 93 %(Group B)

Figure 2, 3 shows the coarse-grained soil rheological curve under different stress level in the compaction degree of 90%. When the stress level is lower (0.2/0.4), rheological deformation develops rapidly at early stage, and it tends to flat finally. When the stress level S=1.0, rheological curve presents an acceleration phase at early stage, the soil has presented a trend of breaking. Rheological curve of compaction degree 93% demonstrate a similar changing regularities.

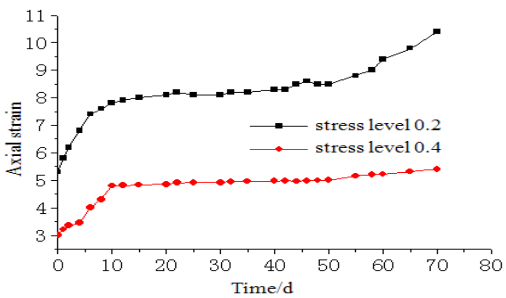

Figure 2: Coarse-grained soil rheological curve (confining pressure 200, stress level 0.2/0.4)

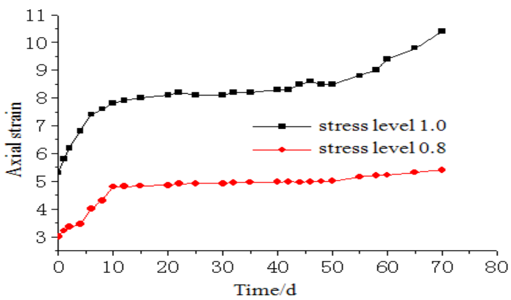

Figure 3: Coarse-grained soil rheological curve (confining pressure 200, stress level 0.8/1.0)

All these tests were fully tamped, the compaction degree reached 90% at least, therefore the sample density is big, and the sample is in a relatively dense state. The confining pressure ranges from 100kPa～300kPa, basically within the limits of lateral stress of highway subgrade. Experimental analysis indicates that the stress level and confining pressure have a significant influence on rheological properties of granular soil embankment. Coarse-grained soil exhibits nonlinear viscoplastic deformation characteristics. From the curves above we can see three rheological phase: decline phase, stable phase, and accelerating failure phase.

4. Settlement prediction of coarse- grained soil embankment

4.1 Settlement composition

Subgrade settlement is composed of compaction deformation of roadbed and foundation settlement, compaction deformation of coarse-grained soil can be controlled by compaction degree, and this part of settlement is almost done at construction stage. Foundation settlement consists of three parts: immediate settlement right after loaded, consolidation settlement because of volume compression caused by drainage of foundation soil, and creep settlement due to secondary consolidation characteristics under the upper load for a long term. Beside the compaction deformation, Coarse-grained soil subgrade still have rheological deformation, which is caused by stress redistribution between particles, rheological deformation can last for years before it reaches stability. For freeway that has high standard for strict post-construction settlement, rheological deformation cannot be neglected.

4.2 Settlement prediction methods

Subgrade settlement prediction consists of two categories: settlement prediction and settlement estimation. Settlement prediction makes use of mathematical model to predict the post-construction settlement based on shape of settling test curve. The latter one is based on geotechnical test to obtain the soil mechanical parameters, and according to empirical formula based on theoretical constitutive model to calculate the settlement, using layer-wise summation method, according to compression modulus Es, e-p curve or e-lgp curve, then multiply by an empirical coefficient to get the total settlement. But empirical formulas haven't considered the historical stress of soil, thus rheological properties of coarse-grained soil subgrade isn't taken into account. Therefore, to calculate total settlement, viscoelastic properties must be considered. Merchant model as one of the viscoelasticity theory can reflect the creep deformation pattern, as well as the instantaneous elastic properties, which is adaptive to analyze the settlement of granular soil subgrade. Formula of Merchant model is:

$$\frac{d\sigma}{dt}+\frac{E_0+E_1}{\eta_1}\sigma=E_0\frac{d\varepsilon}{dt}+\frac{E_0+E_1}{\eta_1}\varepsilon \tag{1}$$

According to the principle of viscoelastic strain superposition, through Laplace transform:

$$\varepsilon=\sigma_0\left[\frac{1}{E_0}+\frac{1}{E_1}-\frac{1}{E_1}\exp\left(-\frac{E_1}{\eta_1}t\right)\right] \tag{2}$$

In the equation, ε—total strain; σ_0—stress, MPa; t—time, d; E_0、E_1—elasticity modulus, Mpa; η_1—viscous coefficient, MPa·d. Combining the right hand sides of Eq (2):

$$\varepsilon=\sigma_0\left\{\frac{1}{E_0}+\frac{1}{E_1}\left[1-\frac{1}{E_1}\exp\left(-\frac{E_1}{\eta_1}t\right)\right]\right\} \tag{3}$$

In Eq (3), the first item of right hand side is instantaneous elastic strain ε_e , the second item is rheological strain ε_c , the relation formula is:

$$\varepsilon=\varepsilon_e+\varepsilon_c \tag{4}$$

The formula of ε_e and ε_c is as below respectively:

$$\varepsilon_e=\frac{\sigma_0}{E_0} \tag{5}$$

$$\varepsilon_c = \frac{\sigma_0}{E_1}\left[1 - \frac{1}{E_1}\exp\left(-\frac{E_1}{\eta_1}t\right)\right] \quad (6)$$

Based on Eq (5) and (6), we get the embankment subsidence. For compaction deformation, use the traditional method to calculate according to Eq (5). For rheological deformation, first, reverse analysis by laboratory rheological test or field test data to obtain the relative calculating parameter, then according to layerwise summation method, rheological settlement of embankment is:

$$S_R = \sum_{i=1}^{n}\frac{\sigma_{0i}}{E_1}\left[1 - \frac{1}{E_1}\exp\left(-\frac{E_1}{\eta_1}t\right)\right]\Delta z_i \quad (7)$$

In the upper formula, S_R -rheological deformation of subgrade; Δz_i -layer thickness; σ_{0i} - layer average selfload stress of subgrade.

5. Verification of an engineering example

This paper utilized K25+320 cross-sections to do the calculation and prediction of settlement as it had a relatively complete settlement observation data, the physical and mechanics parameters of the section are as shown in table 3.

Table 3 physical and mechanics parameters of selected section

Index / Soil layer	Modulus of compression E_0/MPa	Modulus ratio α	Coefficient of viscosity $\eta pa.s$	Poisson's ratio μ	Coefficient of permeability *k/cm/s*
Loam	6.9	1.412	0.06042	0.42	6.94×10^{-6}
Sludge	1.9	0.513	0.01194	0.49	4.56×10^{-7}
Slit clay	7.8	0	0	0.38	9.82×10^{-6}

Based on the established the rheological settlement estimation method above, apply it to the Shaohuai expressway to predict the total settlement, the total settlement is 412mm according to hyperbolic model prediction based on the measured settlement curves, as is shown in figure 4.

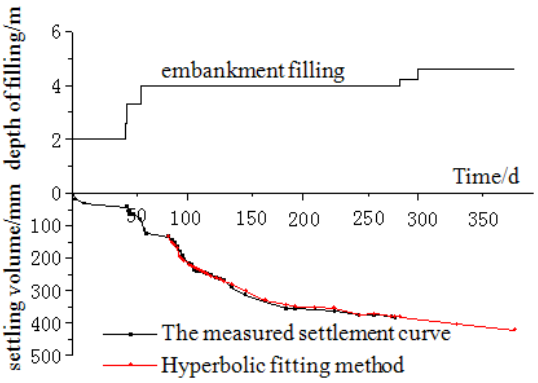

Figure 4: The measured settlement curve and hyperbolic fitting results

The total settlement is 357mm with empirical formula from Code for design of highway subgrade (JTGD30-2004), according to the rheological formula of embankment this article proposed above, the rheological deformation is 31mm, thus the estimated final settlement is 388mm, increased by 8.6%. Civil parameters that the rheological formula needs all come from laboratory tests, but actual settlement is still growing with time, the estimated settlement with rheological deformation is closer to the actual settlement. The method is more accurate, but the calculation parameters are from triaxial test, complicated to obtain, therefore still need to further streamline for engineering application.

6. Conclusions

Aimed at the settlement of embankment in mountainous area caused by rheological deformation of coarse - grained soil, through laboratory experiment and theoretical analysis, the main conclusions and discussions are summarized and presented as follows:

(1) coarse-grained soil embankment settles rapidly during construction stage, it is a good subgrade filling, but its properties is very much influenced by gradation composition, it's possible to redistribute or even break under long-term load, that is rheological deformation, this part of deformation may cause overrun of the post-construction settlement of the subgrade.

(2) Triaxial tests show that stress states have an obvious influence on rheological property of coarse - grained soil embankment. Stress strain curve of coarse-grained soil presents three rheological period: decline phase, stable phase, and Accelerating failure phase.

(3)Settlement calculation method of coarse-grained soil embankment is proposed with rheological deformation taken into account, the method is more conservative compared to empirical method the Specification recommended, but calculating parameters depends on the accuracy of laboratory tests, thus further validation in engineering practice is needed.

Reference

Bagherzadeh-Khalkhali A., Mirghasemi A.A., 2009, Numerical and experimental direct shear tests for coarse --grained soils. Particuology, 7, 83-91, Doi: 10.1016/j.partic.2008.11.006

Bell F.G., 1992, Engineering Properties of Soils and Rocks (Third Edition), Elseviere, Amsterdam, the Netherlands.

Chen X.B., Zhang J.S., Li Z.Y., 2014, Shear behaviour of a geogrid-reinforced coarse --grained soil based on large-scale triaxial tests, Geotextiles and Geomembranes, 42, 312-328, Doi: 10.1016 /j. geotexmem. 2014.05.004.

Cheng Z., Yu J., Ding H., 1999, Experimental Study on Stress-Strain Relationship of Filler for Shuibuya Project's Concrete-Faced Rockfill Dam, Journal of yangtze river scientific research institute, 16,29-32, 10.3969 /j. issn. 1001-5485.1999.01.009(in Chinese).

Deng W., Zhang X., Chen B., 2004. Nonlinear FEM analysis of influence of asphalt pavement under non-homogenous settlement of roadbed[J]. China Journal of Highway and Transport, 7(1):12-15, Doi: 10.3321/j.issn:1001-7372.2004.01.003(in Chinese).

Fargnoli V., Boldini D., Amorosi A., 2013, TBM tunnelling-induced settlements in coarse --grained soils: The case of the new Milan underground line 5, Tunnelling and Underground Space Technology, 38, 336-347, Doi: 10.1016/j.tust.2013.07.015

Fu W., Zheng X., Lei X, et al., 2014, Using a modified direct shear apparatus to explore gap and size effects on shear resistance of coarse --grained soil, Particuology, 23, 82-89, Doi: 10.1016/j.partic.2014.11.013.

Li Z., Li P., 2002, Variation Rule of Shear Strength Index When Direct Shear Test of Coarse --grained Soil, Technique of seepage control, 8, Doi: 10.3969/j.issn.1672-1144.2002.01.003(in Chinese).

Liu H.l., An D., Yang S., 2008, Shear behavior of coarse - aggregates for dam construction under varied stress paths, Water Science and Engineering, 1, 63-77, Doi: 10.1016/S1674-2370(15)30019-3

Liu L., She X., 2006. Study on compaction property of earth-rock mixture, Chinese Journal of Rock Mechanics and Engineering, 25,206-210, Doi: 10.3321/j.issn:1000-6915.2006.01.034 (in Chinese).

Maksimovi M., 1989c, Nonlinear failure envelope for coarse --grained soils. 12th Int. Conf. SMFE, Vol. 1, Rio de Janeiro, Brazil.

Nie L., Wang T., 2015, Analysis of Shear Test on Pile-soil Interface, Chemical engineering transactions , 46, 727-732, Doi: 10.3303/CET1546122

Yang Y., Jiang Y., Wang X., 2016, Pavement Performance Prediction Methods and Maintenance Cost Based on the Structure Load, Procedia Engineering, 137, 41-48, doi: 10.1016/j.proeng.2016.01.232.

Zhang G., Zhang j., 2004, Study on behavior of coarse - grained soil and its modeling, Rock and Soil Mechanics, 25, 1587-1591, Doi: 10.3969/j.issn.1000-7598.2004.10.015(in Chinese).

Zhu G.H., Cheng H., Deng Z.P., Wang Z.G., 2015, Creep Behaviour Analysis and Creep Rupture Prediction of Carbon-glass Fiber Reinforced Polymer Tendon, Chemical engineering transactions, 46,463-468, Doi: 10.3303 / CET1546078