Front. Struct. Civ. Eng. 2018, 12(4): 568–576
https://doi.org/10.1007/s11709-017-0444-4

RESEARCH ARTICLE

Numerical simulation of compaction parameters for sand-filled embankment using large thickness sand filling technique in Jianghan Plain district

Wentao WANG[a], **Chongzhi TU**[b], **Rong LUO**[b*]

[a] *National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China*
[b] *School of Transportation, Wuhan University of Technology, Wuhan 430063, China*
[*] *Corresponding author. E-mail: rongluo@whut.edu.cn*

ABSTRACT The study uses the finite element method to simulate a new technique of highway sand embankment filling in Jianghan Plain district, which can raise the thickness of sand-filled layer from 30 cm to 70 cm and can significantly shorten the construction period based on the guarantee of sand embankment construction quality. After simulating the three compacting proposals carried out on the field test, the study uses COMSOL software to research on the compacting effects of sand-filled layers in larger thicknesses by 22 ton vibratory roller alone, and then to investigate the steady compacting effect of 12 ton vibratory roller. The simulation results indicate that the sand-filled layer thickness of 70 cm is suitable for the new sand filling technique, and the sand-filled embankment project with tight construction period is suggested to choose the 12 ton vibration roller for steady compaction.

KEYWORDS sand embankment, compaction in large thickness, numerical simulation, small size vibratory roller, steady compaction

1 Introduction

As the wide distribution of soft soil foundation in Jianghan Plain district, it's hard to construct highway in this district because of large consumption of farmland soil for higher embankment construction caused by high ground water level, which is not friendly to local environment. In Jianghan Plain district, Yangtze River contains huge sand resources, which can be used as filling materials to construct highway embankment and solve the problem of large soil consumption. Different from dredger-reclaimed sand embankment that can be filled to a large height in one time [1,2], Yangtze River's sand with little mud must be compacted layer by layer in sand embankment construction. However, there is no special specification to instruct sand embankment construction and the thickness of sand-filled layer still refers to the thickness of soil-filled layer from the specifications that should not exceed 30 cm [3,4], which will slow the construction progress and do not match the demand of sand-filled embankment project with tight construction period.

In previous researches, a new technique of highway sand embankment filling was proposed to accelerate construction progress, which could raise the thickness of sand-filled layer from 30 cm to 70 cm and solved the problem of tight construction period caused by soft foundation treatment. After solving the safety problem that vibratory roller was often stuck in wet sand [5], three compacting proposals were carried out on the field test in the sand-filled embankment of highway project from Qianjiang to Shishou and then optimized the compaction parameters [6]. However, it did not further research on larger thickness of sand-filled layer and other compaction pattern combinations as the limitation of construction site condition. In this case, numerical simulation method can be used to solve these issues, and to find out appropriate thickness of sand-filled layer with corresponding compaction parameters, which can significantly shorten the construction period based on the guarantee of sand embankment construction quality and be of great significance to highway sand-filled

Article history: Received Mar 19, 2016; Accepted May 6, 2017

embankment project.

Currently, researches about sand-filled embankment are focused on experimental investigations of different sand soil properties and key points of both design and compacting plan of filling sand embankment and its construction controlling [7–10]. In the aspect of numerical simulations, the analysis of slope stability of sand embankment was conducted with shear strength reduction method [11], and mechanical behavior of fine sand filling embankment was analyzed to optimize its structural system [12], and the settlement characteristics of the sand drain subgrade under embankment load at soft soil area was investigated [13,14]. Additives are used to reinforce embankment and its performance have been evaluated, such as geotechnical performance and field demonstration of highway embankment constructed using waste foundry sand [15], interaction mechanism and behavior of hexagonal wire mesh reinforced embankment with silty sand backfill on soft clay [16], and construction of a test embankment using a sand-tire shred mixture as fill material [17]. Focused on the feature of soft foundation, a lightweight fill for embankments using cement-treated Yangzi River sand and expanded polystyrene beads has been investigated and the parameters from *in-situ* measurements of an embankment on soft clays with sand drains was numerical characterized [18,19]. In consideration of limit fill height of embankment caused by high groundwater level, effect of reinforced sand cushion on soft clay foundation was investigated and a direct shear strength model of river sand was established to evaluate its application in this district [20,21]. Effect of dynamic compaction on red sand soil filling embankment was researched [22], but few on compaction process of filling materials layer by layer using vibratory roller [23–27], and no research on sand compaction process of sand-filled embankment in Jianghan Plain [28].

In this paper, COMSOL finite element software is used to firstly simulate the experimental data of three compacting proposals with the sand-filled layer thickness of 70 cm carried out on the field test for validation of numerical model, and then to investigate the compacting effects of sand-filled layers in larger thicknesses by 22 ton vibratory roller alone and the steady compacting effect of 12 ton vibratory roller. After comparing different compacting proposals, the study recommends applicable sand filling techniques for sand-filled embankment projects with different construction period, and finally compares the large thickness sand filling technique with traditional technique in terms of economic and efficiency.

2 Large thickness sand filling technique and finite element model

The proposed large thickness sand filling technique makes full use of rich resources of sand and gravel from Yangtze River to construct sand-filled embankment in Jianghan Plain district, and the optimized structure of sand-filled embankment are shown in Fig. 1. After laying nonwoven geofabric and two-way geogrid on soft foundation treated by sand cushion, the sandy gravel layer with the thickness of 50 cm is filled directly and a cross slope of 2% is set to make it convenient for water to drain out of embankment structure. The sand-filled layers with the thickness of 70 cm are constructed respectively and surrounded by soil added with 4% lime, which can form a solid structure and avoid collapsing caused by water loss of sand. The roadbed is filled by stoned-added soil, which can raise the stiffness of the embankment structure and reduce the project cost.

The key problem in sand-filled embankment construction is lack of bearing capacity for sand caused by water content of being too high or too low, which may get the vibratory roller stuck in sand and both slow the construction speed and cause hidden trouble to safety. According to the sand's California Bearing Ratio tests conducted in different water content [29], the maximum values of sand's CBR and dry density occurred in the optimum water content and increased with the growth of compaction level, which indicated that the denser of sand and the higher bearing capacity it had. Further, the test that water content

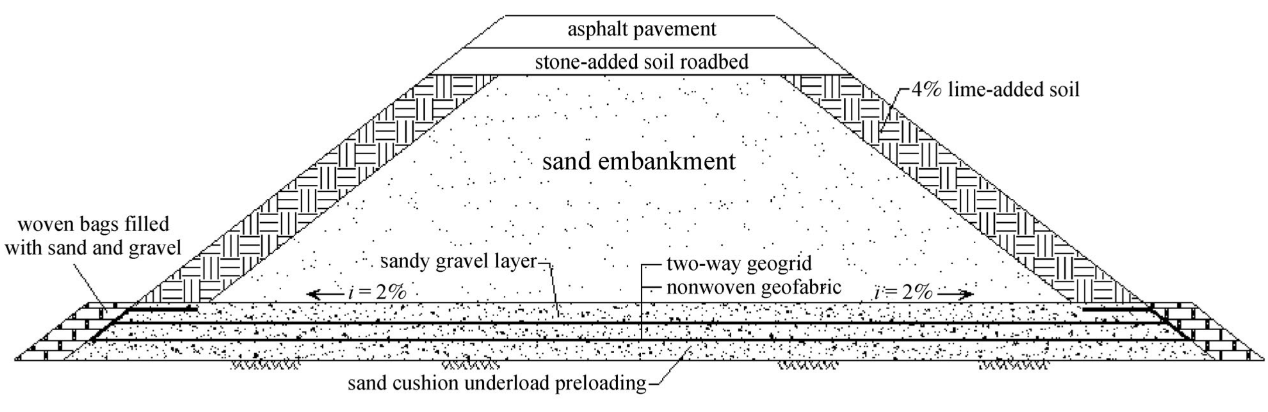

Fig. 1 Optimized structure of sand-filled embankment

of sand changed with time were conducted to find the waiting time for sand to reach its optimum water content in different weather and condition, which supplied data for sand filling construction site to avoid machine getting stuck in wet sand and ensure the construction safety.

When sand is in optimum water content, apply an appropriate compaction pattern combination to the sand-filled layer and raise its bearing capacity step by step can finally make the compaction degree meet the specification. The construction processes of embankment using large thickness sand filling technique are shown in Fig. 2. Firstly, watered the sand-filled layer sufficiently and controlled sand water content to the optimum state by manual watering. Then raised the bearing capacity of the sand-filled layer by loader machine, which could create a safe construction condition for 22 ton vibratory roller to compact on sand-filled layer without getting stuck in wet and loose sand. Applied appropriate pattern combinations of weak and strong vibratory compaction by 22 ton vibratory roller to raise the bearing capacity of sand-filled layer step by step, and finally checked the compaction degree in upper, middle and lower layer respectively [30]. According to results from field tests [6], the large thickness sand filling technique could avoid machine getting stuck in wet sand and raised the thickness of sand-filled layer from 30 cm to 70 cm, which could significantly shorten the construction period based on the guarantee of sand embankment construction quality.

In order to break the limitation of construction site condition and further find out appropriate thickness of sand-filled layer with corresponding compaction parameters for sand-filled embankment in Jianghan Plain district, the study focuses on larger thickness of sand-filled layer and other compaction pattern combinations to numerical simulation. As a powerful finite element software with its friendly interactive interface [31–33], COMSOL is widely used for simulation analysis in subgrade engineering and pavement engineering [34–40], which is chosen for numerical simulation in this study. The study chooses one of the sand-filled layers from 93% compaction degree demanded district in embankment construction site to simulate the sand compaction process in large thickness of sand-filled layer. As a compacted sand-filled layer does not affect the construction process of next sand-filled layer and the vibratory roller compacts the sand layer from one side to other side, the width dimension of the sand model is chosen as approximately the same width as the Roller's vibratory drum. Moreover, sand is thought at its optimum water content, which makes it possible for vibratory roller not to get stuck in sand. As shown in Fig. 3, it is the two dimensional finite element model of sand-filled layer with the thickness of 70 cm and the width of 2.5 m. The model with the fixed constraint in the bottom and the free constraint in two sides is meshed by triangular. A numerical linear elastic model is used to simulate the sand, and the material parameters are shown in Table 1.

Two types of single-drum vibratory rollers are chosen to

Fig. 2 Construction process of embankment using large thickness sand filling technique

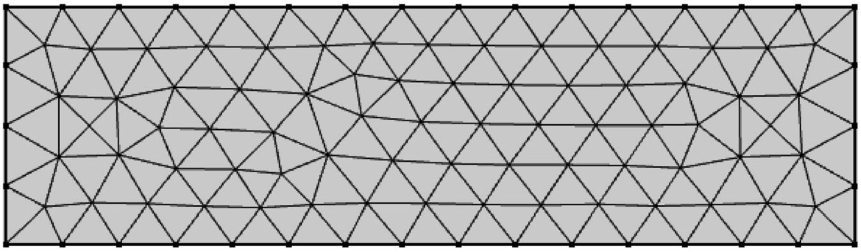

Fig. 3 Finite element model of sand-filled layer

Table 1 Sand parameters for finite element model

sand filling layer thickness (cm)	elasticity modulus (MPa)	Poisson's ratio	wet density before compacting (g/cm^3)	maximal dry density (g/cm^3)	optimum water content (%)
70/80/90/100	39.173	0.3	1.765	1.78	15.8

apply several compaction pattern combinations to the sand-filled layer model, which includes static compaction, weak vibratory compaction and strong vibratory compaction. The parameters of single-drum vibratory rollers are shown in Table 2. In order to simplify the simulation process, the load applied to the sand model is Roller's maximum vibratory load when it is passing the cross section of the sand-filled layer as shown in Fig. 3.

3 Simulation and analysis for compaction process of sand-filled layer using 22 ton vibratory roller

Applying several compaction pattern combinations to sand-filled layer with the thickness of 70 cm by the 22 ton vibratory roller, and then check the compaction degree whether it meets the specification. As the compaction degrees decline with depth in sand-filled layer, the study chooses the compaction degree of the bottom sand layer as the test index.

Simulated compaction degrees of three compacting proposals carried out on the field test are shown in Table 3, which indicates that weak vibratory steady compaction promotes the improvement of sand compaction degree to some extent and strong vibratory compaction has an obvious effect on enhancing the compaction degree of the sand-filled layer. The combinations of weak and strong vibratory compaction in proposal 1 and proposal 2 have better effect than the sustained weak vibratory compaction

Table 2 Parameters of single-drum vibratory rollers

Roller's model	Roller's mass (kg)	vibratory drum's mass (kg)	vibratory drum's diameter (m)	vibratory drum's width (m)	vibration frequency (Hz)	vibration force (kN)
22 ton	22000	11000	1.6	2.13	29/35	390/258
12 ton	12000	7000	1.5	2.13	32/36	280/178

Table 3 Simulated compaction degrees of three compacting proposals carried out on the field test (%)

proposal 1	static compaction 1st	weak vibratory compaction 1st	strong vibratory compaction 1st	strong vibratory compaction 2nd	strong vibratory compaction 3rd	strong vibratory compaction 4th
field test	88.2	88.9	90.7	92.7	92.9	93.2
simulation	86.3	87.1	88.5	89.8	91.3	92.8
proposal 2	static compaction 1st	weak vibratory compaction 1st & 2nd	strong vibratory compaction 1st	strong vibratory compaction 2nd	strong vibratory compaction 3rd	strong vibratory compaction 4th
field test	88.2	89.2	91.5	93.0	93.2	93.5
simulation	86.3	88.0	89.3	90.7	92.2	93.7
proposal 3	static compaction 1st	weak vibratory compaction 1st & 2nd	weak vibratory compaction 3rd	weak vibratory compaction 4th	weak vibratory compaction 5th	weak vibratory compaction 6th
field test	88.3	90.4	90.8	91.6	91.7	91.9
simulation	86.3	88.0	88.8	89.7	90.5	91.4

combination in proposal 3. Both the simulation and field test data of proposal 2 can meet the demand of 93% compaction degree in the specification [3,4], which indicates that using the combinations of weak and strong vibratory compaction to improve the bearing capacity of sand-filled layer step by step can economically meet the demand of sand filling construction in large thickness and guarantee the sand embankment construction quality. Although there are some differences between simulations and field test data, the final compacting effects of proposals stay the same tendency at last, which indicates the reliability of the sand model.

Further, compaction parameters of proposal 2 are chosen to explore the compacting effect in larger thicknesses of sand-filled layers, such as 80 cm, 90 cm and 100 cm. The simulation results are shown in Fig. 4, which indicates that the compaction degrees decline with the depth in sand-filled layer at the fourth time of strong vibratory compaction, and the sustained strong vibratory compaction are needed to meet the demand of 93% compaction degree in the specification. In addition, the sand filling progress needs to match the progress of surrounding soil filling which should not exceed the thickness of 30 cm according to the specification [3,4], and 70 cm is finally chosen as the thickness of sand-filled layer for embankment construction.

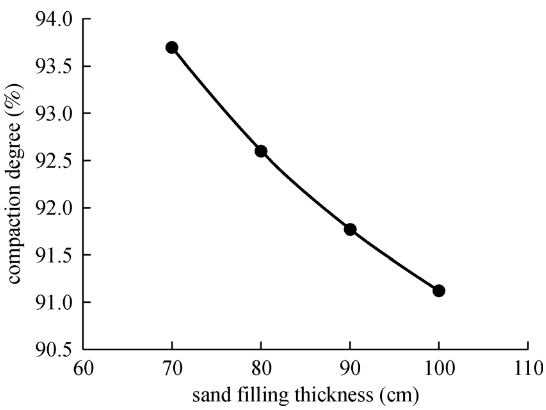

Fig. 4 Compaction degrees in different thicknesses of sand-filled layers

4 Simulation and analysis for compaction process of sand-filled layer using 12 ton vibratory roller

The key problem in sand-filled embankment construction is lack of bearing capacity for sand caused by water content of being too high or too low, which might get the vibratory roller stuck in sand and cause hidden trouble to safety. Applying weak vibratory steady compaction to sand-filled layer to improve its bearing capacity by 22 ton vibratory roller, and then using strong vibratory compaction can reinforce the compaction degree to meet the specification [6]. However, previous research did not explore the steady compacting effect of small size vibratory roller as the limitation of construction site condition, which has been discussed in this study and stated below.

Simulated compaction degrees of different proposals combined with steady compaction by 12 ton vibratory roller and strong vibratory compaction by 22 ton roller are shown in Table 4, which indicates that strong vibratory steady compaction by 12 ton roller is effective to enhance the bearing capacity of sand-filled layer and can match the effect of weak vibratory steady compaction by 22 ton roller. Compared with proposal 2, the compaction degrees of the bottom sand layer in proposal 5 can also meet the specification at the same compaction times, which indicates that the compacting effect of compaction pattern combinations by 12 ton and 22 ton vibratory roller are basically the same as by 22 ton vibratory roller alone from the simulative perspective.

Table 4 Simulated compaction degrees of 70 cm sand filling thickness using 12 ton vibratory roller for steady compaction (%)

Roller's model	12 ton		22 ton	
proposal 4	weak vibratory compaction 1st	strong vibratory compaction 1st	strong vibratory compaction 4 times	-
compaction degree	86.2	87.0	92.6	-
proposal 5	weak vibratory compaction 1st	strong vibratory compaction 1st & 2nd	strong vibratory compaction 4 times	-
compaction degree	86.2	87.9	93.6	-
proposal 6	weak vibratory compaction 1st	strong vibratory compaction 1st	weak vibratory compaction 1st	strong vibratory compaction 4 times
compaction degree	86.2	87.0	87.9	93.6
proposal 7	weak vibratory compaction 1st	strong vibratory compaction 1st	weak vibratory compaction 1st & 2nd	strong vibratory compaction 4 times
compaction degree	86.2	87.0	88.7	94.5

5 Comparison between different sand compacting proposals and economic analysis

5.1 Comparison between different sand compacting proposals

Only steady compact the sand layer for enough bearing capacity by using some compaction pattern combinations can make it possible for 22 ton vibratory roller to start strong vibratory compaction without being stuck in wet sand. When sand-filled layer is at the state of optimum water content, the steady compacting effect of strong vibratory compaction by 12 ton roller is basically the same as weak vibratory compaction by 22 ton roller, which can both reach the demanded compaction degree in relatively less compacting times. As shown in Fig. 5, the 22 ton vibratory roller might get stuck in wet sand as the lack of sand bearing capacity if the water content is a little higher than optimum state, but the 12 ton vibratory roller can be used in this construction condition to improve sand bearing capacity and create construction condition for 22 ton vibratory roller.

In different construction weather and environmental conditions [5], there is a waiting period for sand-filled layer to reach optimum water content after being sufficiently watered, such as half a day in breeze and cloudy weather. Therefore, combinations of weak and strong vibratory compaction by 22 ton vibratory roller alone are suggested for the sand-filled embankment project with rich construction period, such as proposal 2 in Table 3. However, combinations of steady compaction by 12 ton vibratory roller coordinated with strong vibratory compaction by 22 ton roller are strongly recommended for the sand-filled embankment project with tight construction period caused by time consumption of soft soil foundation treatment or other reasons, such as proposal 5 in Table 4. Although the recommendations concerned with 12 ton vibratory roller will increase some project cost in early construction, but it can insure the rollers against getting stuck in wet sand later, which can significantly shorten the construction period based on the guarantee of sand embankment construction safety and quality.

5.2 Economic analysis of sand-filled technique

Compared with traditional thickness sand filling technique that each sand-filled layer's thickness should not exceed 30 cm, the large thickness sand filling technique proposed in this paper has more than double thickness of each sand-filled layer, which can largely speed up the process of embankment filling and shorten the construction period. In order to compare the construction cost of the two techniques, 22 ton vibratory roller is chosen for compaction alone and each construction process is taken into account, which includes transportation, paving, watering and compaction. The cost of sand transportation process is calculated by the actual number of sand transport trucks, which means that the large thickness sand filling technique will not have extra cost in this process. It takes about two days to water sand-filled layer and wait to reach its optimum water content, and both two techniques have the same cost. In compaction process, it takes about eight times of sustained weak vibratory compaction for traditional technique to reach the demanded compaction degree of 93%, which takes about six times of weak and strong vibratory compaction for large thickness sand filling technique to reach, but the fuel consumption of vibratory roller for the two techniques are more or less the same. In this case, the difference of construction cost for the two techniques is mainly in the paving process.

As shown in Fig. 1, a sand-filled embankment with height of 5 m and length of 100 m is chosen to calculate the construction cost of the two techniques. The trapezoid embankment section is equivalent to a rectangle section with the same area, which assumes that the width of each

Fig. 5 Vibratory roller of 22 ton was stuck in wet sand when compacting

sand-filled layer stays the same. Construction periods and cost of the two techniques' paving process are calculated according to the highway engineering budget quota [41], and the compaction coefficient of sand-filled layer is 1.2. As shown in Table 5, the construction cost of the traditional thickness sand filling technique is almost the same as the large thickness sand filling technique, but the latter can save the construction period by 59 d which makes significant economic benefits.

Table 5 Economic analysis and comparison between large thickness sand filling technique and traditional sand filling technique

compared items	traditional technique	proposed technique
thickness per layer (cm)	30	70
number of layers	20	9
time consumption of construction processes per layer (d)		
transportation	2	3
paving	2	3
watering	2	2
compaction	1	1
total per layer	7	9
total construction period (d)	140	81
sand-filled quantity per layer (m^3)	880.5	2054.5
paving cost		
bulldozer	1533 yuan/1000 m^3	
loader	985 yuan/1000 m^3	
cost per layer (yuan)	2217.1	5173.2
total construction cost (yuan)	44342.0	44334.6

The large thickness sand filling technique makes full use of abundant resource of Yangtze River's sand to construct sand-filled embankment in Jianghan Plain district, which can significantly accelerate the construction speed based on the guarantee of the sand embankment construction quality and reduce negative effects caused by construction to local traffic and environment. The environmental advantage of the proposed technique is that it utilizes river sand which has to be removed to retain the profile of the river bed and also be of great importance to the improvement of channels in Yangtze River. Moreover, the saved construction period can be used for soft foundation preloading treatment, which can reduce both the differential settlement after construction and the possibility of pavement distresses appeared widely after traffic opening.

6 Summary and conclusions

The main objective of this paper is to find out better sand filling techniques to save construction period and guarantee construction quality by simulating the sand compaction process in large thickness of sand-filled layer for highway sand-filled embankment project in Jianghan Plain district. Based on the results presented in this paper, the following key findings are offered:

(1) The simulation results of weak and strong vibratory compaction combinations and the sustained weak vibratory compaction combination are compared with the field test data, which shows the same tendency in conclusions and indicates that using the combinations of weak and strong vibratory compaction to improve the bearing capacity of sand-filled layer step by step can economically meet the demand of sand filling construction in large thickness and guarantee the sand-filled embankment construction quality.

(2) Sustained strong vibratory compaction by 22 ton roller is needed for larger thickness of sand-filled layers to meet the demanded compaction degree. In order to match the progress of surrounding soil filling, 70 cm is finally chosen as the thickness of sand-filled layer for embankment construction.

(3) Strong vibratory steady compaction by 12 ton roller is effective to enhance the bearing capacity of sand-filled layer and can match the effect of weak vibratory steady compaction by 22 ton roller.

(4) Combinations of weak and strong vibratory compaction by 22 ton vibratory roller alone are suggested for the sand-filled embankment project with rich construction period. However, for the sake of shortening the waiting period after sand-filled layers being sufficiently watered and insuring the construction safety, combinations of steady compaction by 12 ton vibratory roller coordinated with strong vibratory compaction by 22 ton roller are strongly recommended for the sand-filled embankment project with tight construction period.

(5) The construction cost of the traditional thickness sand filling technique is almost the same as the large thickness sand filling technique, but the latter can save a lot of the construction period which makes significant economic benefits.

(6) The simulated conclusions in this study need further validation in practical sand-filled embankment project in future.

References

1. Han C, Lin G, Peng X. Study on the technology of high fill subgrade in deep water. Highway, 2012, (7): 57–60
2. Deng M. Research on dynamic compaction of foundation of blowing sand reclamation. Highway, 2012, 29(7): 11–13
3. Ministry of Transport of the People's Republic of China. JTG D30-2004 Specification for Design of Highway Subgrades. Beijing: China Communication Press, 2004

4. Ministry of Transport of the People's Republic of China. JTG F10-2006 Technical Specification for Construction of Highway Subgrades. Beijing: China Communication Press, 2006
5. Fang Z, Li L, Liu Z, Luo R, Feng G. Characterization of the compaction and bearing strength of the Yangtze sand. Journal of Wuhan University of Technology, 2016, 40(3): 550–553
6. Wang W T, Dong H, Luo R, Jin L, Zeng W, Feng G. Research on the compaction parameters of sand-filled embankment using larger thickness technology in Jianghan Plain. Journal of Wuhan University of Technology, 2016, 40(6): 998–1002
7. Jiang X, Ling J, Li J. Some critical problems on sand embankment design for expressway. Chinese Journal of Underground Space and Engineering, 2011, (6): 570–575
8. Hua-Fu R, Ye H C, Su K. On the design and compacting plan of filling sand embankment and its construction controlling key points. China Municipal Engineering, 2009, 5
9. Yao Y. Research on subgrade compaction and quality control measures of Yingshuang Highway. Dissertation for the Master's Degree. Xi'an: Changan University, 2012
10. Qu M, Xie Q, Cao X, Zhao W, He J, Jin J. Model test of stone columns as liquefaction countermeasure in sandy soils. Frontiers of Structural and Civil Engineering, 2016, 10(4): 481–487
11. Liu S T, Cao W D, Li Y Y, Yang Y S. An analysis of slope stability of sand embankment with shear strength reduction method. Advanced Materials Research, 2010, 152-153: 1017–1023
12. Zhang H, Meng G L, Lv Y J. Analysis of optimum structural system and mechanical behavior of fine sand filling embankment. Applied Mechanics and Materials, 2011, 94–96: 95–98
13. Ren H. An analytical study on consolidation settlement characteristics of the sand drain (wall) subgrade under embankment load at soft soil area. Railway Standard Design, 2003
14. Luo J, Shen L. Deformation analysis of sand embankment considering soft foundation consolidation settlement. Highway Engineering, 2016, 2: 147–151
15. Partridge B K, Fox P, Alleman J, Mast D. Field demonstration of highway embankment constructed using waste foundry sand. Transportation Research Record: Journal of the Transportation Research Board, 1999, 1670(1): 98–105
16. Bergado D T, Youwai S, Teerawattanasuk C, Visudmedanukul P. The interaction mechanism and behavior of hexagonal wire mesh reinforced embankment with silty sand backfill on soft clay. Computers and Geotechnics, 2003, 30(6): 517–534
17. Yoon S, Prezzi M, Siddiki N Z, Kim B. Construction of a test embankment using a sand-tire shred mixture as fill material. Waste Management (New York, N.Y.), 2006, 26(9): 1033–1044
18. Wang F, Miao L. A proposed lightweight fill for embankments using cement-treated yangzi river sand and expanded polystyrene (eps) beads. Bulletin of Engineering Geology and the Environment, 2009, 68(4): 517–524
19. Cancelli A, Cividini A. An embankment on soft clays with sand drains numerical characterization of the parameters from *in-situ* measurements. International Conference on Case Histories in Geotechnical Engineering, 1984, 1
20. Liu H. FEM analysis of deformation for stratified rolling and filling of high fill subgrade. Science and Technology Information, 2011, 7: 241–242
21. Wei L M, Niu J D, Huo H J. Effect of reinforced rand cushion on the limit fill height of embankment on soft clay foundation. Geosynthetics in Civil and Environmental Engineering, 2009, 261–265
22. Chen C. Effect of dynamic compaction on red sand soil filling embankment. Applied Mechanics and Materials, 2012, 268-270(1): 788–791
23. Cui X, Yao Z, Guo Y. The theory and technology of Yellow River road. Beijing: Science Press, 2016, 116–129
24. Liu S, Zhang N, Cao W, Li Y. Establishment of direct shear strength model of river sand and its application in high embankment of sand. International Conference on Electric Technology and Civil Engineering, 2011, 297–302
25. Xu H, Zhou F. Three dimensional finite element simulation analysis of high speed railway subgrade compaction. Subgrade Engineering, 2007, 6: 241–242
26. Cao Z Y. Road engineering properties of metamorphic soft rock used as embankment filling in Qin-Ba mountain areas and vibration compaction technology research. Dissertation for the Doctoral Degree. Xi'an: Changan University, 2013
27. Xiang L. Research on relationship between the vibration acceleration of vibratory roller and the degree of soil compaction. Dissertation for the Master's Degree. Chongqing: Chongqing Jiaotong University, 2012
28. Huang H, Zhang Z. Research on surrounding soil construction timeliness of sand-filled embankment in soft soil foundation of Jianghan Plain. Transportation Science and Technology, 2014, 5: 74–75
29. Ministry of Transport of the People's Republic of China. JTG E40-2007 Test Methods of Soils for Highway Engineering. Beijing: China Communication Press, 2007
30. Ministry of Transport of the People's Republic of China. JTG E60-2008 Field Test Methods of Subgrade and Pavement for Highway Engineering. Beijing: China Communication Press, 2008
31. Ge Z, Wang H, Zheng L, Mao H L. Properties of concrete containing recycled clay brick powder. Journal of Shandong University, 2012, 42(1): 104–105
32. Ge Z, Huang D, Sun R, Gao Z. Properties of plastic mortar made with recycled polyethylene terephthalate. Construction & Building Materials, 2014, 73: 682–687
33. Ge Z, Yue H, Sun R. Properties of mortar produced with recycled clay brick aggregate and pet. Construction & Building Materials, 2015, 93: 851–856
34. Hou Y, Wang L B, Yue P, Pauli T, Sun W. Modeling mode I cracking failure in asphalt binder by using nonconserved phase-field model. Journal of Materials in Civil Engineering, 2014, 26(4): 684–691
35. Hou Y, Sun W, Huang Y, Ayatollahi M, Wang L B, Zhang J. Diffuse interface model to investigate the asphalt concrete cracking subjected to shear loading at a low temperature. Journal of Cold Regions Engineering, 2017, 31(2): 04016009
36. Hou Y, Wang L B, Wang D, Liu P, Guo M, Yu J. Characterization of bitumen micro-mechanical behaviors using AFM, phase dynamics theory and MD simulation. Materials (Basel), 2017, 10(2): 208
37. Hou Y, Guo M, Ge Z, Wang L B, Sun W. Mixed-mode I-II cracking characterization of mortar using phase-field method. Journal of Engineering Mechanics, 2017, 143(7): 04017033

38. Xu H N, Guo W, Tan Y Q. Internal structure evolution of asphalt mixtures during freeze-thaw cycles. Materials & Design, 2015, 86 (12): 436–446
39. Xu H N, Guo W, Tan Y Q. Permeability of asphalt mixtures exposed to freeze-thaw cycles. Cold Regions Science and Technology, 2016, 123(3): 99–106
40. Xu H N, Tan Y Q, Yao X A. X-ray Computed Tomography in hydraulics of asphalt mixtures: Procedure, accuracy, and application. Construction & Building Materials, 2016, 108(4): 10–21
41. Ministry of Transport of the People's Republic of China. JTG/T B06-02-2007 Highway Engineering Budget Quota. Beijing: China Communication Press, 2007