Vibration test study on aeolian sand filler of existing slab culvert strengthened by corrugated metal pipe

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Abstract. Inadequate structural bearing capacity has appeared in the Reinforced Concrete (RC) slab culverts in permafrost regions of China which have experienced degradation, and need to meet new codes or standards. Based on the method of strengthening for culvert structure by the corrugated metal pipe (CMP), in this paper, shaking table test and vibration box test were introduced to study the vibrational compactness of aeolian sand filled in the small space between the CMP and existing culvert. The results show that aeolian sand in drying or near saturation can be better compacted; aeolian sand with a higher water content has a lower optimum vibration frequency; the sand within 0.6 m from the vibrator can be effectively compacted and 0.4m is the best; in the vibration frequency range of 50~110 Hz, the modulus of aeolian sand decreases as the frequency increases.

1. Introduction

Reinforced cement (RC) slab culvert is widely used in National Highway 214 built in the 1980s because of its simple construction. But now these RC slab culverts required to carry higher loads and become more fatigued compared to how they were originally designed. According to field investigations, due to the processes of abrasion and corrosion, the slab culvert is in a state of deterioration that requires restoration. The restoration of the existing infrastructure is a worthwhile solution compared to undertaking a total replacement of these structures because it is typically much faster and easier to reduce the economic and environmental impact on highway network disruption [1].

The installation of a new internal pipe inside the existing culvert is a repair measurement that has received considerable attention from researchers. The CMP and culvert structures must share the load though the filling material. The filling material can be sand, “sand-cement” mixtures, grout and flowable fill, or concrete mixtures which depend on the type of structure, void area, strength requirements, and equipment available for the work.

It is well established that the modified sand in the space between the pipe and the existing culvert could provide uniform support. There are substantial benefits resulting from taking modified sand as filler while maintaining superior flexibility of the overall reinforcement structure. A technique for filling annular voids between the culvert and the CMP is closely associated with this problem in the minds of engineers [2].

Soil modification aims to improve its characteristics, and quite a few mechanical or chemical methods have been explored over years. Standard Proctor test is usually to ascertain compaction characteristics of a soil as optimum moisture content and maximum dry density [3]. Chemically modified soil refers to soil mixed with organic or inorganic binder, such as cement, lime, etc. These inorganic additives can give the soil higher compression and tensile strength, better cohesion and better water resistance, thus improving its stability [4-5].
Mechanically modified sand achieved by vibration or impact has been successfully employed in engineering construction, and stress waves are generated to rearrange the soil particles into a denser state [6-9].

In general, the choice of a stable method is influenced by the properties of the material to be stabilized and the field construction circumstances. In this project, cement modified aeolian sand filling the void space between the existing culvert and the newly placed CMP. The sand filler is compacted by a distinctive vibration device that is attached to the inner wall of the CMP. In this paper, the vibration compaction characteristics of cement modified aeolian sand in narrow space are studied by shaking table and vibration box tests.

2. Project overview
The project involved in this article is located at National Highway 214 in Qinghai Province, China, where, the development of frozen soil causes a large amount of ground deformation. Moreover, aeolian sand are ubiquitous material in this area. Therefore, using CMP and modified sand as a method of rehabilitation and strengthening of RC slab culverts is proposed and investigated here. Care must be taken to ensure that the CMP and existing slab culvert structures share the load. It is well established that when old culverts begin to collapse, there is danger of point loads and deflection, and the filler in the space between the outside diameter of the pipe being installed and the existing culvert can prevent concentrated loads.

3. Laboratory tests
Before using aeolian sand as filler in the narrow space between the RC slab culvert and CMP, the degree of compactness and strength are required to reach the level specified by the code. Ideally, the sand between the existing culvert and the CMP must always be uniform and dense to strengthen deficient structures. For this purpose, electrodynamic oscillators attached to the inner surface of the CMP are used during the construction process to help the sand flow well to fill the small gaps and obtain a higher density. Shaking table tests and vibrating box tests are employed to examine the compaction characteristics of the aeolian sand used in the control of field construction process.

3.1. Materials
The aeolian sand used in the laboratory tests is extracted from National Highway 214 in Qinghai Province, China. The grain size distribution of aeolian sand ranges from 0.075 to 2 mm and has no cohesive forces and no plasticity. According to the grain size distribution indexes: Cu=2.44 and Cc=0.88 were ascertained by the curve, these sands were defined as uniformly grained soil (even-graded according to Highway Geotechnical Test Procedure JTGE40—2007).

3.2. Test design
Vibrational compaction characteristics of a soil, such as the optimum moisture content (OMC), optimal compaction frequency and maximum dry density were investigated by a self-designed and customized shaking table (see figure 1).

Nine compaction molds were fixed on the table with an electrodynamic oscillator mounted near it. The molds have the exact same internal dimensions as a CBR mold with a diameter of 152 mm and height of 170 mm. A certain volume of aeolian sand was placed in the steel cylinder mold, and its weight of 3.6 kg could be utilized to produce a constant pressure on the upper surface. The sands were divided into ten kinds of samples according to the moisture content (ranging from 0% to 18%) and then shaken for 3 minutes on a shaking table with an amplitude of 0.4 mm and 7 kinds of frequencies, ranging from 40 Hz to 100 Hz. The penetration resistance of the sample was determined by a micor-penetrometer, and then a dry oven was used to determine the dry density.
A vibrating box with inner measurements of 1 m by 1 m by 1 m (W by L by H) as shown in Fig.2 was specially designed and constructed at the Key Laboratory of Ministry of Education for Special Regional Highway Engineering, Chang’an University, to study the influence range of the attached oscillator on sand. The specified sinusoidal displacement characterized by a given frequency was implemented with the help of frequency-variable oscillators.

In particular, the rubber sheets were designed between the oscillator panel and other panels to eliminate the influence of the oscillator on the three adjacent panels. Furthermore, a water filter and a drain valve were provided at the bottom of the vibrating box. The frequency could vary from 30 to 180 Hz by adjusting the frequency-variable oscillators.

Vibrating box tests were performed with a frequency of 30 Hz to 180 Hz. The penetration resistance (expressed by DCPI) of the sand in different layers in the box was measured by the dynamic cone penetrometer (DCP). The typical DCP consists of an 8-kg hammer that drops over a height of 575 mm, which yields a theoretical driving energy of 45 J or 14.3 J/cm² and drives a 60° cone tip with a 20 mm base diameter vertically into the soil sample to be tested [16]. Then the number of drops and penetration depth during the operation were recorded to derive the DCP penetration index (DPI). The density and resilient modulus of each layer were estimated according to the empirical formula, and the dry density of the layered sampling sand was obtained by the cutting ring method. The resilient modulus (Es) is defined as:

\[ E_s = 537.76 \times DPI^{-0.6645} \] (1)

4. Results and discussion

4.1. Effects of the water content and particle size on the compactness

The results of the shaking table test are shown in Figure 3, which presents a rule that whether the sand is dry sand or saturated, the penetration resistance will decrease with increasing particle size. From the overall situation of the two lines, the penetration resistance of dry aeolian sand is much smaller than that of saturated sand. The particles of dry sand are very loose and the penetration resistance is mainly caused by friction. In addition to friction, the water-glue interaction will contribute to the penetration resistance because of the common binding water film surrounding the particles in the saturated sand.
When the variable is the moisture content, the penetration resistance and dry density curve show two peaks, as shown in Figure 4 and Figure 5, respectively. In view of this phenomenon, we also draw a scatter plot of the penetration resistance (Y) and dry density (X), and it is found that they have a correlation with a correlation coefficient (Pearson’s r) of 0.97 based on the following function:

\[ r(X, Y) = \frac{\text{cov}(X, Y)(\text{Var}[X]\text{Var}[Y])^{1/2}}{\text{Var}[X]\text{Var}[Y]} \]  

where X represents the dry density, Y represents the penetration resistance, and r (X, Y) represents the correlation coefficient.

The mechanism of vibration compaction can be described as follows: when sand is dry, the frictional resistance between the particles is smaller, thus it is easier to reach a dense state under vibration and pressure; however, the addition of water increases the cohesion between particles due to capillary action and the formation of a water film with a certain viscosity, elasticity and shear resistance. Then the thickness of the water film increases and the capillary effect disappears with a further increase in water content. At this time, water plays a role in reducing the cohesion of the particles to obtain the maximum penetration resistance or dry density; in the end, too much water occupies the pores between the particles, resulting in a decrease in the dry density and penetration resistance.
4.2. Distribution of the effect of the vibrator on the sand

Figure 6a shows the evolution of the rebound modulus of the sample against the depth (from the top of the box) for different horizontal distances (from the vibrating plate) with a moisture content of 8% and vibration frequency of 50 Hz. The result after changing the frequency to 80 Hz is presented in Figure 6b. As seen from these figures, the closer to the vibrator, the higher the compactness will be while the range of influence of the vibrator is approximately 0.4~0.6 m, and 0.3~0.4 m is the substantial area.

In the actual structure, the distance between the CMP and the slab culvert is range from 0.4m to 0.5m, thence the thickness of the aeolian sand filler is also in this range. Therefore, the filling material can achieve better vibration density in actual engineering.

A comparison was added (see Figure 7) between the modulus of the saturated sand along the depth range at different horizontal distances when the vibration frequency is 50 Hz. The comparison shows that the sand in the range of 0~0.5 m from the vibrator can reach a rebound modulus of 30~40 MPa, which is close to the bearing capacity of the subgrade according to the code.

4.3. Effect of the vibration frequency on the sand

According to the shaking table test, as the vibration frequency increases, the density of the sand gradually increases. When the frequency exceeds the optimum frequency, the increase in the frequency will be expected to result in a decrease in the density. Dry sand and saturated sand with a water content of 14% have different optimum vibration frequencies corresponding to the maximum dry density (see Figure 8).
Figure 8. Dry density of aeolian sand with two water contents at different frequencies in a shaking table test.

In addition, when the horizontal distance is 12 cm and 22 cm, the data at the three frequencies (50 Hz, 80 Hz and 110 Hz) are compared together (see Figure 9a and Figure 9b) and we can find that after the frequency exceeds 50 Hz, the rebound modulus and the vibration frequency are negatively correlated.

Figure 9. The variation of rebound modulus of river sand at horizontal distance of 12 cm (a) and 22 cm (b) when the vibration box was set to three frequencies.

5. Conclusion

(1) From the results of the shaking table test, aeolian sand, as a non-cohesive soil, can be better compacted at the time of drying or near saturation. Moreover, the correlation analysis shows a good correlation in aeolian sand between the dry density and penetration resistance.

(2) The dry density has a positive impact on the penetration resistance. The water content has a substantial effect on the optimum vibration frequency to such an extent that sand with a higher water content has a lower optimum frequency.

(3) From results of the vibration box tests, the aeolian sand within 0.6 m from the vibrator can be effectively compacted, and the moisture can improve the compaction efficiency of the vibrator.

(4) The closer the aeolian sand is the oscillator, the greater the density will be. Within 0.6 m from oscillator, the density can be substantially improved, and within 0.4 m is better. The modulus of aeolian sand filler can meets the requirements of the specification after conversion.

(5) In terms of the vibration frequency, in the frequency range of 50–110 Hz, the elastic modulus decreases as the vibration frequency increases. Laboratory tests will be of great help to choosing water content and vibration frequency during field construction.
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