Study on Water Sinking Sand Method for Sand Backfilling

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Abstract: Based on the partial culvert backfilling project of the JI-HEI Expressway construction in Heilongjiang Province, China, this study investigates the impact of the physical and mechanical characteristics of backfill sand on the compaction degree of sand backfilled using the water sinking sand method. The research includes on-site sampling of the backfill sand, indoor geotechnical testing, water sinking sand method backfilling, and compaction degree testing of the backfilled material. The study explores the particle size distribution, moisture content, density, compaction characteristics, California Bearing Ratio (CBR), rebound modulus, and other physical and mechanical attributes of the sand. It also delves into the water sinking sand method backfilling process and the compaction degree of the soil layer after backfilling. The findings indicate that the backfill sand in this project is a loose, medium to coarse sand with a low moisture content. Its maximum dry density is approximately 1.92 g/cm³, and the optimal moisture content is around 8%. When the sand reaches maximum dry density, both CBR value and rebound modulus reach their highest levels. The reduction in rebound modulus of the sand is not significant, suggesting good water stability. The actual compaction degree of the soil layer achieved through water sinking sand method backfilling ranges from 96% to 99%, meeting the compaction requirements of conventional engineering practices. The application of the water sinking sand method for sand backfilling is characterized by its simplicity, high construction efficiency, and quality assurance, making it suitable for widespread adoption in future engineering projects.

Keywords: Water Sinking Sand Method; Backfill Sand; Physical Mechanical Characteristics; Compaction Characteristics; Compaction Degree.

1. Introduction

In highway engineering, there are numerous specialized locations, such as bridge and culvert abutments, various structural foundation pits, ditches, and so on. During backfill construction, conventional large-scale compaction equipment is not suitable for these areas. Additionally, these aforementioned locations typically have higher requirements for compaction density during backfilling. Therefore, it is necessary to employ specific construction techniques. The water sinking sand method, also known as water-shaking grit[1], is characterized by its long history in craftsmanship and reliable quality. It finds widespread application in construction projects such as highway engineering [2,3], hydraulic engineering[4], and municipal pipeline construction[5,6]. The construction process of the water sinking sand method utilizes the fluidity of water and the permeability of sand, and through additional vibrational force, it causes the movement and rearrangement of sand particles in water. Fine sand fills the voids among coarse sand, thereby achieving a compacted state[7]. This process is simple to operate, highly efficient in construction, and comes with quality assurance. Typically, the compaction degree of backfill can reach 95%, and it does not result in significant settlement[2,8].

However, existing research mainly focuses on the detailed construction procedure of this method[9–11]. There is a scarcity of research on the movement patterns of backfill sand during the layering process in the water sinking sand method, as well as the influence of different types of backfill sand on the compaction degree achieved through this method. In this paper, based on a section of culvert backfilling in the Ji-Hei Expressway construction project in Heilongjiang Province, China, samples of backfill sand were collected from the site. Through indoor geotechnical tests and on-site compaction degree measurements, the study investigates the impact of the physical-mechanical properties on the compaction degree achieved during the water sinking sand method for backfilling.

2. Physical-Mechanical Properties of Backfill Sand

The physical-mechanical properties of backfill sand directly influence the backfill construction process and its quality, as well as the overall performance of the structure. In this section, experimental research will be conducted on the physical properties, compaction characteristics, and static properties of backfill sand.

2.1 Study of the Physical Properties of Backfill Sand

The collected backfill sand samples were initially subjected to an exploration of their physical properties. The experimental content primarily encompassed particle size distribution analysis, moisture content, particle specific gravity, and compactness. The on-site obtained backfill sand samples are illustrated in Figure 2-1:

Figure 2-1: On-Site Collection of Backfill Sand Samples

2.1.1 Analysis of Particle Size Composition

The particle size composition analysis of backfill sand follows the Chinese standard "Test Methods of Soils for Highway Engineering"[12] (JTG 3430-2020). Six sets of backfill sand samples from different batches were collected for testing. Particle size analysis was conducted using a 500g sample through vibrational sieving. The sieving results representing the samples are shown in Table 2-1, and the particle size distribution curve is illustrated in Figure 2-2.

Table 2-1: Sieving Results of Representative Samples

Sieve Aperture Size (mm)	Sand on Sieve (g)	Retained Fraction (%)	Cumulative Retained (%)	Passing Rate (%)
9.5	0	0	0	100
4.75	16.8	3.27	3.27	96.73
2.36	40.8	7.94	11.20	88.80
1.18	114.7	22.31	33.51	66.49
0.6	103.3	20.09	53.61	46.39
0.3	129.5	25.19	78.80	21.20
0.15	99.5	19.35	98.15	1.85
0.075	7.3	1.42	99.57	0.43
<0.075	2.2	0.43	100	0

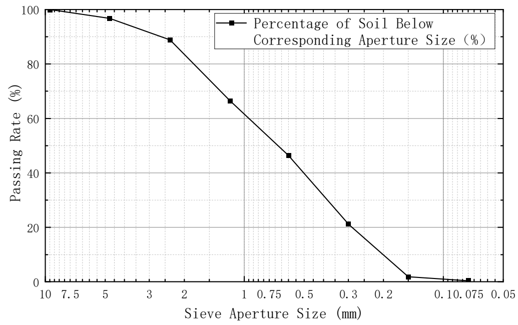

Figure 2-2: Particle Size Distribution Curve of Representative Samples

From this, the two particle size distribution indices for each sample can be determined: the uniformity coefficient (C_u) and the curvature coefficient (C_c). The calculation formulas are as follows:

$$C_u = \frac{d_{60}}{d_{10}} \quad (2\text{-}1)$$

$$C_c = \frac{d_{30}^2}{d_{60} \times d_{10}} \quad (2\text{-}2)$$

In the equations, d_{60}, d_{30}, and d_{10} respectively represent the particle sizes corresponding to the cumulative percentage passing of 60%, 30%, and 10%. The calculated results for the six sets of samples are shown in Table 2-2.

Table 2-2: Uniformity Coefficient and Curvature Coefficient of Backfill Sand Samples

Index	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
C_u	4.651	4.398	4.477	4.486	4.641	4.458	4.518
C_c	0.774	0.782	0.773	0.747	0.764	0.859	0.783

Based on the particle size analysis results and in accordance with the standards outlined in JTG 3430-2020, the backfill sand in question is categorized as poorly graded, medium to coarse sand.

2.1.2 Determination of Moisture Content

The moisture content of soil is the ratio of the mass of water to the mass of solid particles in the soil. Following the guidelines of standard JTG 3430-2020, an experiment was conducted using the oven-drying method. Each backfill sand sample, weighing 50g, was placed in a container (20g), and dried for 6 hours at a constant temperature of 105-110°C. The results of the moisture content tests for backfill sand are presented in Table 2-3.

Table 2-3: Results of Backfill Sand Moisture Content Determination

Box Number (Sample)	1	2	3	4	5	6
Mass of Box + Dry Soil (g)	69.05	68.97	68.84	69.01	68.97	69.09
Mass of Water (g)	0.95	1.03	1.16	0.99	1.03	0.91
Mass of Dry Soil (g)	49.05	48.97	48.84	49.01	48.97	49.09
Moisture Content (%)	1.9	2.06	2.32	1.98	2.06	1.82
Average Moisture Content (%)	2.02					

Based on the experiments, it can be determined that the moisture content of this backfill sand is relatively low, approximately around 2%.

2.1.3 Determination of Specific Gravity

The particle specific gravity refers to the ratio of the mass of dry soil particles at a constant weight between 105°C and 110°C to the mass of an equal volume of pure water at 4°C. Following the guidelines of standard JTG 3430-2020, an experiment was conducted using the specific gravity bottle method with distilled water. The results of the specific gravity tests for backfill sand samples are presented in Table 2-4.

Table 2-4: Results of Specific Gravity Determination for Backfill Sand Samples

Sample	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Specific Gravity	2.52	2.55	2.53	2.54	2.54	2.54

Based on the experiments, it can be determined that the specific gravity of this backfill sand is approximately in the range of 2.52 to 2.55, indicating a sandy soil composition.

2.1.4 Determination of Compaction Characteristics (Standard Penetration Test)

For the determination of compaction characteristics of backfill sand, in-situ tests were conducted using the standard penetration test. Following the guidelines of the Chinese standard "Code for Design of Building Foundation"[13] (GB 50007-2011), a 63.5kg hammer was dropped freely from a height of 76cm, driving a standard penetration apparatus with dimensions of 51cm length, 5.1cm outer diameter, and 3.49cm inner diameter, into the soil to a depth of 30cm. The number of hammer blows required for this penetration, known as the standard penetration value (N) was recorded.

Based on the field tests, the standard penetration value (N) for the backfill sand falls within the range of 7 to 10. According to the provisions of the standard GB 50007-2011, the compaction level of the backfill sand can be categorized as a loose state.

2.2 Study of Compaction Characteristics of Backfill Sand

This study aims to investigate the compaction characteristics of backfill sand and determine the optimal compaction effectiveness that can be achieved. Following the guidelines of standard JTG 3430-2020, the maximum dry density of backfill sand was determined using the compaction method. This experiment employed the heavy compaction method. The results of the compaction test for backfill sand samples are presented in Table 2-5, and the compaction curve is illustrated in Figure 2-3.

Table 2-5: Results of Heavy Compaction Test for Backfill Sand

Test Number	1	2	3	4	5	6	7	8
Average Moisture Content (%)	0	1.89	4.15	5.82	7.97	10.22	12.08	14.91
Dry Density (g/cm³)	1.891	1.881	1.895	1.906	1.915	1.911	1.907	1.895

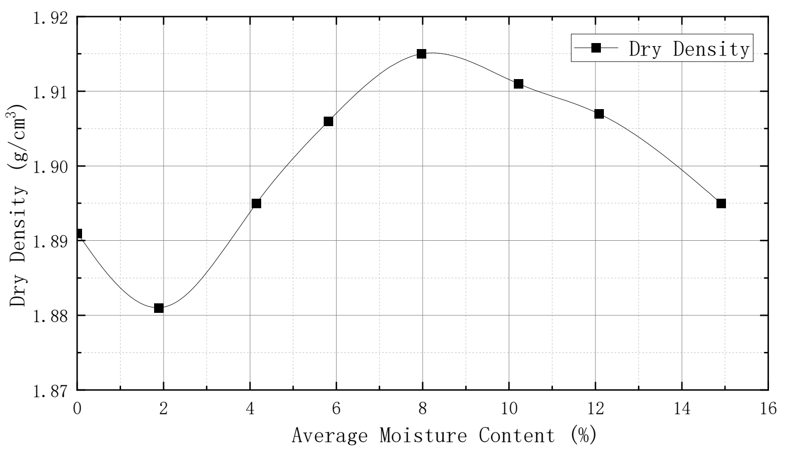

Figure 2-3: Compaction Curve of Backfill Sand

Test Results:	The maximum dry density is approximately 1.92 g/cm³, and the optimal moisture content is around 8%.

Based on the experiments, it can be concluded that the compaction curve for the backfill sand follows a horizontal "S" shape. When the backfill sand is dry, its dry density reaches a peak value. As its moisture content increases, the dry density initially decreases. Within the moisture content range of 2% to 8%, the dry density gradually increases. It reaches its peak value at around 8% moisture content. Within the range of 8% to 15% moisture content, the dry density gradually decreases. From the compaction curve, it's apparent that the maximum dry density for this backfill sand is approximately 1.92 g/cm³.

2.3 Study of Mechanical Properties of Backfill Sand

The mechanical properties of backfill sand directly impact the overall stability of the entire project. In this study, the mechanical properties of backfill sand are investigated from two perspectives: California Bearing Ratio (CBR) and modulus of backfill. These angles are chosen to analyze the mechanical characteristics of the backfill sand.

2.3.1 Determination of California Bearing Ratio (CBR)

The CBR determination of backfill sand is conducted following the guidelines of standard JTG 3430-2020. The CBR test results for backfill sand samples are presented in Table 2-6.

Table 2-6: Results of CBR Test for Backfill Sand

Dry Density (g/cm³)	1.915	1.903	1.877	1.832	1.780
CBR (%)	26.2	22.0	18.4	16.4	13.8

Based on the experiments, it can be inferred that as the dry density of backfill sand increases, the CBR value demonstrates a noticeable rise. The CBR value reaches its maximum near the maximum dry density, which corresponds to the optimal moisture content. As the dry density increases, the volume of pores within the sand per unit area reduces, resulting in a substantial enhancement of the overall load-bearing capacity of the sand.

2.3.2 Determination of Resilient Modulus

The determination of the resilient modulus of backfill sand is conducted following the guidelines of standard JTG 3430-2020. The resilient modulus test results for backfill sand samples are presented in Table 2-7.

Table 2-7: Results of Resilient Modulus Test for Backfill Sand

Dry Density (g/cm³)	1.915	1.903	1.877	1.832	1.780
Resilient Modulus (%)	62.2	58.3	56.9	54.7	50.4

Based on the experiments, it can be observed that the resilient modulus of backfill sand increases with the rise in dry density. The resilient modulus value reaches its peak near the maximum dry density, which corresponds to the optimal moisture content. In comparison to silty and clayey soils, the reduction in the resilient modulus of backfill sand is relatively weak, indicating good water stability.

Through the California Bearing Ratio (CBR) and resilient modulus tests, it is evident that when the backfill sand reaches its maximum dry density, both the CBR and resilient modulus attain their peak values. This backfill sand exhibits favorable mechanical properties.

3. Water-Sinking Sand Method for Sand Backfill Construction and Compaction Degree Testing

Utilizing the sand studied in the previous section, backfilling for the abutment of culverts is carried out using the water-sinking sand method. Subsequently, compaction degree testing is conducted to evaluate the level of compaction achieved.

3.1 Principles of Water-Sinking Sand Method for Backfilling

The principle of the water-sinking sand method for backfilling is as follows: The loose accumulation of sand particles can be hypothetically envisioned as irregularly sized spherical particles, chaotically piled together with voids in between, forming a cohesive entity through the restraint of internal friction. Upon wetting the surface of the loose sand with water, buoyancy generated counteracts a portion of the sand's gravitational force, reducing the squeezing pressure between the sand particles. Simultaneously, water infiltration plays a lubricating role between the sand particles, forming a water film on their surfaces that reduces internal friction.

Moreover, the introduction of water displaces gaseous components within the sand system. As water enters, propelled by its inherent force and the formation of air bubbles, the equilibrium of the sand system is disrupted, initiating motion. At this stage, by incorporating tamping or vibrating rods and applying manual vibration, the motion of the sand system intensifies. The flow of water also becomes turbulent due to the added external vibration and sand particle movement.

Under the repeated influence of hydraulic flow, external vibration forces, and the buoyant effect of air bubbles, sand particles of various sizes adjust their positions and orientations iteratively, compacting each other. The faster flow velocity and lower pressure in small voids cause smaller sand particles to be continually pressed into the gaps of larger sand particles. This process increases the contact area and friction resistance between the particles, gradually leading to rational compaction. When the sand particle assembly is reasonably compact (i.e., dense), higher energy is required to disrupt it. In contrast, when the assembly is inadequately compacted (i.e., loose), the contact area and friction resistance between sand particles are reduced, requiring less energy for disruption, thus making it easier to break apart.

Continuously subjected to external forces, the sand system evolves through a cycle of disruption, equilibrium, re-disruption, and re-equilibrium. This gradual progression leads the sand particles toward a state of rational compaction, forming a relatively dense structure. Subsequently, during drainage, water infiltrates the voids, further consolidating smaller sand particles. Additionally, as the water level recedes, the entire sand system experiences settling, enhancing the overall compaction of the backfill system.

3.2 Water-Sinking Sand Method for Sand Backfilling

The specific on-site construction process of the water-sinking sand method is as follows:

1.Preparation of Materials, Machinery, and Personnel:

This includes gathering the required materials such as sand backfill, a water source, an insert-type compaction rod, a water pump, drainage facilities (wells or drainage pipes), a generator set, and skilled technicians.

2.Site Preparation:

Prior to initiating the backfilling work on the abutment and backwall, the concrete strength of the bridge and culvert walls that have already been constructed must reach at least 80%. The site where backfilling will take place should be examined to determine if the bearing capacity of the foundation meets requirements. If it doesn't, remedial measures such as replacement of unsuitable soil are needed to ensure proper foundation bearing capacity. The foundation should be compacted, manually leveled, and well-prepared with proper cofferdams and drainage facilities in place.

3.Layered Sand Backfilling:

Utilizing a loader and manual labor, the sand backfill material is distributed and evenly spread, with each layer being around 50cm thick. The surface is smoothed, and markers are placed according to the compaction radius to indicate the compaction points.

4.Water Injection and Compaction:

Using a water pump, water is poured onto the sand backfill material. The water level should be maintained slightly above the top surface of the sand backfill. Once water has been adequately added, the compaction rod is inserted. The compaction rods are inserted with a spacing of not more than 30 cm along diagonal lines. During the compaction process, the compaction rod should be moved up and down. When performing compaction in layers with water sinking, the compaction rod should penetrate into the layer below to ensure continuity between two adjacent layers. Each compaction point should be treated for at least 40 seconds, until the sand surface no longer sinks and there are no air bubbles emerging, and the surface becomes level. During compaction, additional water can be added as needed, based on changes in the water level on the surface of the sand.

5.Layered Water Sinking Construction:

The compaction should be carried out uniformly and comprehensively for each layer. After compacting each layer of sand, it is necessary to have a designated person observe the settlement values of the sand layer and the water level. When the settlement stabilizes, water content and compaction degree tests should be arranged. If the compaction degree meets the requirements, steps 3 and 4 can be repeated to build the next layer. This process is repeated layer by layer to complete the water sinking method of sand backfill construction.

6.Drainage and Compaction Degree Testing:

After completing the backfilling of all layers with sand, proceed with drainage work. Once the water is drained, conduct compaction degree testing on the backfilled area.

3.3 Backfill Compaction Degree Testing

After the water sedimentation method backfill is completed, the primary quality indicator to be assessed is the compaction degree. Instruments and methods used to determine the compaction degree of the sand backfill can be categorized into two types: destructive testing and non-destructive testing.

Destructive Testing: Destructive testing methods include the ring knife method and the sleeve sand pouring method. These methods involve removing a sample from the backfill for testing purposes, which may impact the integrity of the backfill structure.

Non-Destructive Testing: Non-destructive testing methods include the falling weight method, surface wave method, and nuclear density method. These methods allow for compaction assessment without disturbing the backfill.

Considering the construction site conditions, the ring knife method will be employed for compaction degree testing in this test section. This method involves removing a cylindrical sample from the compacted backfill and measuring its weight and volume to calculate the compaction degree.

The compaction degree of the ring knife method is determined by comparing the measured in-situ dry density obtained from field ring knife sampling with the maximum dry density measured in the laboratory. On the surface of the site after completing the water-sediment sand filling using the water sedimentation method, remove the surface floating soil, place the ring knife, and use a hammer to strike the ring knife into the soil to complete the sampling. A total of 5 soil samples are taken. Refer to the provisions of JTG 3430-2020 for testing. The calculation method for the construction compaction degree of the backfilled sand is as follows:

$$K = \frac{\rho_d}{\rho_{d\max}} \times 100\%, \quad (3\text{-}1)$$

$$\rho_d = \frac{\rho}{1 + 0.01\omega} \quad (3\text{-}2)$$

Where: K as the construction compaction degree, %; ρ_d the dry density of the compacted sample, g/cm³; $\rho_{d\max}$ as the maximum dry density obtained from the experiments is 1.92 g/cm³; ρ as the wet density of the sample, g/cm³; ω the moisture content of the sample, %. The results of the tests are presented in Table 3-1:

Table 3-1: Results of Backfill Compaction Degree Testing (Ring Knife Method)

Sample Type	1	2	3	4	5
Ring Knife + Soil Weight (g)	571.4	575.8	573.1	576.6	580.2
Ring Knife Weight (g)	171	170.5	171	170.5	171
Sample Weight(g)	400.4	405.3	402.1	406.1	409.2
Ring Volume (cm^3)	200.00	200.00	200.00	200.00	200.00
Wet Density (g/cm^3)	2.00	2.03	2.01	2.03	2.05
Moisture Content (%)	8.3	8.4	8.3	8.4	8.4
Dry Density (g/cm^3)	1.85	1.87	1.86	1.87	1.89
Maximum Dry Density (g/cm^3)	1.92	1.92	1.92	1.92	1.92
Compaction Degree (%)	96.5	97.5	96.8	97.8	98.5

From this, it can be observed that the actual compaction degree of the soil layer formed by the backfilled sand using the water-sinking sand method ranges between 96% and 99%, meeting the compaction requirements of typical engineering backfilling. This also indicates that the use of the water-sinking sand method for backfilling sand, as employed in this study, is a reliable construction technique that ensures high-quality compaction.

4. Conclusion

This study is based on the partial culvert backfill project of the JI-HEI Expressway construction in Heilongjiang Province, China. It investigates the influence of the physical and mechanical characteristics of backfill sand on the compaction degree of backfilled sand using the water sinking sand method. The following conclusions were drawn:

1. The backfill sand is loose and has a relatively low moisture content, categorizing it as a medium to coarse sand. The maximum dry density is approximately 1.92 g/cm³, and the optimal moisture content is around 8%. Near the maximum dry density, the CBR value and rebound modulus of the backfill sand reach their highest values. Additionally, the reduction in rebound modulus of the backfill sand is not significant, indicating good water stability.

2. The actual compaction degree of the soil layer achieved through water sinking sand backfilling of the backfill sand is between 96% and 99%, which meets the requirements for conventional compaction in engineering. It is evident that the water sinking sand method for backfilling is a reliable construction process.

The application of water sinking sand method for sand backfilling can result in a compact backfilled layer, ensuring high construction efficiency and quality assurance. This method holds promising prospects for a wide range of applications, including filling behind bridge abutments, trench backfilling, and backfilling of pipeline foundation pits, among other engineering projects.

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