Experimental Study on Zoning Characteristics of Soft Soil Blasting Disturbance in Sea Embankment Foundation

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Abstract. The current research on the mechanism of blasting compaction mainly focuses on how to form a rockfill dam under the action of blasting load, but there is little research on the dynamic response characteristics of soft soil media under blasting. In blasting compaction of deep silt, it is necessary to pay attention to the damage and disturbance effect of explosive explosion on the surrounding soft soil medium, thereby providing new ideas for the study of blasting compaction mechanism of deep silt. With a seawall project in Huizhou as a prototype, based on the blasting similarity theory and through a generalized model and parameter similar design, experimental research on deep silt blasting compaction centrifuge was carried out in a 200g-t centrifuge. The physical and mechanical parameters of the silt soft soil at different positions were acquired through testing before and after the blasting, and property changes of the soft soil medium were analysed under the explosion to speculate disturbance range of the soft soil medium under the explosion effect, and divide the different blasting disturbance areas. The test results provide data support for the optimization of the design parameters of the seawall project, and also provide a useful reference for the study on the blasting compaction mechanism of deep silt and similar engineering practices.

1. Introduction
In recent years, with the rapid development of national economy and society, our ports, water conservancy, and transportation projects have developed vigorously. Our coastal areas such as the Bohai Bay, the Yangtze River Delta, and the Pearl River Delta have complex and changeable geological conditions, where marine sedimentary soft soils are widely distributed, with thicknesses ranging from several meters to tens of meters. Soft soil foundation has the characteristics of high water content, high compressibility, low strength, low permeability, sensitive structure, etc., and its physical and mechanical properties are poor. As one of the most effective foundation treatment methods in the construction of silt seawall engineering, blasting compaction technology has been widely used in large projects such as Lianyungang Port in Jiangsu Province and Yantian Port Cofferdam Project in Shenzhen[1-2]. Many factors affect the blasting compaction. With its theoretical research lagging behind engineering practice, improvement is needed in test approaches and research methods, and engineering applications rely more on engineering experience [3]. The research on the physical and mechanical properties of the silt soft soil itself and the dynamic response characteristics of the soft soil under the action of explosion has become the key to the study of the blasting compaction mechanism of deep silt.
The centrifugal test technology simulates gravity through centrifugal force to achieve the same stress state as the prototype. By making the model and the prototype have equal stress and similar deformation, it simulates the deformation and failure process, and achieves the effect of on-site prototype testing. The explosion energy in the centrifugal simulation field has a 1:n^3 scale relationship with the prototype. In the centrifugal field, small explosion energy is needed to simulate the explosion effect of a large-energy prototype [4-5]. Therefore, the centrifuge test enjoys significant advantages in simulating the blasting effect. The former Soviet Union Pokrovsky and Fedorov, et al. conducted a series of centrifuge crater studies, determined the scale of the explosion centrifugal model, verified the empirical formula of the explosion crater, and used the explosion model test to simulate the explosion of the atomic bomb. Hou Yujing et al. [6] summarized the principles of explosive centrifugal model tests and the research methods and results of some foreign scholars. It is believed that the use of centrifugal model tests to study geotechnical problems under explosion and impact loads has unique advantages, which can not only simulate prototype gravity conditions, but also simulate the larger explosion effect of the prototype based on energy scale relationship. Zhang Xuedong et al. [7] used a centrifugal model to study the impact of blasting on the dam by stimulating the prototype stress, mainly considering the impact of detonator blasting on the dam under different gravitational accelerations, different water depths, and different distances from the dam surface. Ma Liqiu et al. [8] summarized several key issues of the explosion centrifugal model test, including model box, explosion source, centrifugal model scale, data acquisition, Coriolis acceleration, etc.; developed a centrifugal model explosion test system to study shallow buried circle structure under the surface explosion.

With a seawall project in Huizhou as a prototype, based on the blasting similarity theory and through a generalized model and parameter similar design, experimental research on deep silt blasting compaction centrifuge was carried out in a 200g-t centrifuge. The physical and mechanical parameters of the silt soft soil at different positions were acquired through testing before and after the blasting, and property changes of the soft soil medium were analysed under the explosion to speculate disturbance range of the soft soil medium under the explosion effect, and divide the different blasting disturbance areas. The test results provide data support for the optimization of the design parameters of the seawall project, and also provide a useful reference for the study on the blasting compaction mechanism of deep silt and similar engineering practices.

2. Test overview

This test takes a seawall project in Huizhou Port as a prototype. The model box has a dimension (length × width × height) of 1.0 m × 1.0 m × 1.0 m. Three-dimensional simulation of the blasting compaction model test was carried out, with operating acceleration of the centrifuge at 80g. So far, the depth of blasting mud displacement in the blasting compaction embankment construction is generally between a dozen meters and tens of meters. Centrifuge was used in this test to prepare the model with foundation depth of 50 cm, which is equivalent to the depth of 40m under the prototype conditions.

In this test, No. 8 instant power detonator was used as the explosion source, with a single detonator converted into about 1.0g TNT equivalent (equivalent to 512kg under the prototype condition). To achieve off-site control of detonation under the centrifuge operating conditions, the explosion ignition device was designed and installed for the centrifuge system in this test. The relay was controlled by the controller to turn on and off the current source and thereby realize the purpose of ignition and detonation.

Table 1 shows the basic physical parameters of the model soil samples used in this experiment. It can be seen from Table 1 that the soil sample has a plasticity index IP=16.9%, and the soil sample is silty clay. The optimal moisture content \(w_{opt}=20.5\%\), and the maximum dry density \(\rho_{max}=1.67\, \text{g/cm}^3\).

| Particle grading (%) | \(w_P\) | \(w_L\) | \(w_{opt}\) | \(\rho_{max}\) (g/cm\(^3\)) |
|----------------------|-------|-------|---------|-----------------|
|                      | mm    | mm    | mm      | 0.075~0.5       |
|                      |       |       |         | 0.075~0.005     |
|                      |       |       |         | <0.005          |
| 0.075~0.5 mm         | 16.2  | 33.1  | 20.5    | 1.67            |
| 0.075~0.005 mm       |       |       |         | 14.1            |
| <0.005 mm            |       |       |         | 54.5            |
|                      |       |       |         | 31.4            |

Table 1. Basic physical properties of model soil
The test is divided into two groups. The test (MDB1) with an explosive burial depth of 8.0cm (corresponding to 6.4 m in the prototype) under 80g and blasting compaction test (MDB2) on foundation soils with different moisture contents at explosive burial depth of 10cm (corresponding to 8.0 m in the prototype) were carried out. Before blasting compaction, conduct soil tests on density, water content, and cross plate shear to obtain the physical and mechanical parameters of silt soft soil; after blasting compaction, take samples from different areas around the explosion center point to perform corresponding soil test before explosion. Compare the changes of the silt soil physical and mechanical parameters before and after the explosion. The sampling point is 5, 10, 15, 20, 25 cm away from the explosion center point. The actual sampling position can be adjusted appropriately according to the conditions of the centrifuge model test.

3. Analysis of test results

3.1. MDB1 test results

Figure 1 is a schematic diagram of measuring points about dry density, water content and undrained strength after MDB1 blasting test. The preparation of the foundation soil has a water content of 40%, and a double-shot detonator with a burial depth of 8cm (corresponding to the prototype depth of 6.4m) was set. Table 2 is a statistical table of soil dry density and moisture content after MDB1 test, and Table 3 is a statistical table of soil cross-plate shear strength after MDB1 blasting test.

![Figure 1. Layout of silt strength and water content test](image-url)

| number | distance from explosive source (cm) | dry density (g/cm³) | water content(%) | number | distance from explosive source (cm) | dry density (g/cm³) | water content(%) |
|--------|-----------------------------------|---------------------|------------------|--------|-----------------------------------|---------------------|------------------|
| WH1    | 5                                 | 1.48                | 49.5             | WV1    | 5                                 | 1.49                | 48.3             |
| WH2    | 10                                | 1.49                | 45.3             | WV2    | 10                                | 1.50                | 43.0             |
| WH3    | 15                                | 1.51                | 41.3             | WV3    | 15                                | 1.52                | 41.0             |
| WH4    | 20                                | 1.50                | 40.0             | WV4    | 20                                | 1.50                | 43.5             |
Table 3. MDB1 Statistics of the non drainage strength after explosion

| number | distance from explosive source(cm) | Undrained strength (KPa) | number | distance from explosive source(cm) | Undrained strength (KPa) |
|--------|-----------------------------------|--------------------------|--------|-----------------------------------|--------------------------|
| SH1    | 5                                 | 5.0                      | SV1    | 5                                 | 5.1                      |
| SH2    | 10                                | 12.4                     | SV2    | 10                                | 13.1                     |
| SH3    | 15                                | 14.9                     | SV3    | 15                                | 15.3                     |
| SH4    | 20                                | 15.2                     | SV4    | 20                                | 15.3                     |
| SH5    | 25                                | 15.1                     | SV5    | 25                                | 15.4                     |

It can be seen from Table 2 and Table 3 that: with the increase of the distance between WH1~5 measuring points and the explosion center in the horizontal direction, the soil dry density increases from 1.48g/cm³ to 1.51g/cm³ within 5~15cm from the explosion center point, with water content reduced from 49.5% to 41.3%, and undrained shear strength increased from 5.0KPa to 14.9KPa, while the soil dry density, water content and undrained strength do not change significantly at 15cm beyond the explosion center. With the increase of the distance between WH1~5 measuring points and the explosion center in the vertical direction, the soil dry density increases from 1.49g/cm³ to 1.52g/cm³ within 5~15cm from the explosion center point, with water content decreased from 48.3% to 41.0%, and undrained shear strength increased from 5.1 KPa to 15.3KPa, while the soil dry density, water content and undrained strength do not change significantly at 15cm beyond the explosion center.

The test results show that the double-shot detonator in this blasting test has an impact range of about 15cm (equivalent to 12.0m in the prototype soil). Where: in the range of 0~5cm (corresponding to 0~4m in the prototype), the undrained shear strength of the soil is significantly reduced after blasting, indicating that the soil within 0~5cm from the explosion center point undergoes process similar to liquefaction under the explosion impact. This area can be classified as first-level blasting disturbance zone. Within the range of 5~10cm (corresponding to 4~8m in the prototype), the undrained shear strength of the soil is reduced by about 25% after the blasting. This area can be classified as second-level blasting disturbance zone. Within the range of 10~15cm (corresponding to 8~12m in the prototype), the undrained shear strength of the soil is reduced by about 15% on average after the blasting, and the area can be classified as third-level blasting disturbance zone. Given a range beyond 15cm (beyond 12.0m range in the prototype soil), the soil physical and mechanical parameters have not changed, which can be considered that there is basically no disturbance.

3.2. MDB2 test results

The foundation soil of the MDB2 model was prepared with a water content of 40%, and a three-shot detonator with a burial depth of 10cm was set. After the blasting test, the locations of the measuring points for dry density, water content and undrained strength are shown in Figure 1. Table 4 is a statistical table of soil dry density and water content after MDB2 blasting test, and Table 5 is a statistical table of soil cross-plate shear strength after MDB2 blasting test.

Table 4. Statistical table of dry density and water content after MDB2 explosion

| number | distance from explosive source (cm) | dry density (g/cm³) | water content(%) | number | distance from explosive source (cm) | dry density (g/cm³) | water content(%) |
|--------|-----------------------------------|---------------------|------------------|--------|-----------------------------------|---------------------|------------------|
| WH1    | 5                                 | 1.48                | 51.2             | WV1    | 5                                 | 1.47                | 52.0             |
| WH2    | 10                                | 1.48                | 49.5             | WV2    | 10                                | 1.48                | 48.5             |
| WH3    | 15                                | 1.49                | 45.5             | WV3    | 15                                | 1.50                | 46.3             |
| WH4    | 20                                | 1.49                | 43.1             | WV4    | 20                                | 1.51                | 43.2             |
| WH5    | 25                                | 1.50                | 40.0             | WV5    | 25                                | 1.53                | 40.3             |
Table 5. MDB2 Statistics of the non drainage strength after explosion

| number | distance from explosive source(cm) | Undrained strength (KPa) | number | distance from explosive source(cm) | Undrained strength (KPa) |
|--------|-----------------------------------|--------------------------|--------|-----------------------------------|--------------------------|
| SH1    | 5                                 | 4.5                      | SV1    | 5                                 | 4.4                      |
| SH2    | 10                                | 9.6                      | SV2    | 10                                | 10.1                     |
| SH3    | 15                                | 14.2                     | SV3    | 15                                | 14.5                     |
| SH4    | 20                                | 14.9                     | SV4    | 20                                | 15.1                     |
| SH5    | 25                                | 15.2                     | SV5    | 25                                | 15.2                     |

It can be seen from Table 4 and Table 5 that: with the increase of the distance between WH1~5 measuring points and the explosion center in the horizontal direction, the soil dry density increases from 1.48 g/cm³ to 1.50 g/cm³ within 5~20 cm from the explosion center point, with water content reduced from 51.2% to 40.0%, and undrained shear strength increased from 4.5KPa to 14.9KPa, while the soil dry density, water content and undrained strength do not change significantly at 20cm beyond the explosion center. With the increase of the distance between WV1~5 measuring points and the explosion center in the vertical direction, the soil dry density increases from 1.47 g/cm³ to 1.53 g/cm³ within 5~20 cm from the explosion center point, with water content decreased from 52.0% to 43.3%, and undrained shear strength increased from 4.4 KPa to 15.1KPa, while the soil dry density, water content and undrained strength do not change significantly at 20 cm beyond the explosion center.

The test results show that the three-shot detonator in this blasting test has an impact range of about 20cm (equivalent to 16m in the prototype soil). Where: in the range of 0~5 cm (corresponding to 0~4 m in the prototype), the undrained shear strength of the soil is significantly reduced after blasting, indicating that the soil within 0~5 cm from the explosion center point undergoes process similar to liquefaction under the explosion impact. This area can be classified as first-level blasting disturbance zone. Within the range of 5~10 cm (corresponding to 4~8 m in the prototype), the undrained shear strength of the soil is reduced by about 33% after the blasting. This area can be classified as second-level blasting disturbance zone. Within the range of 10~20 cm (corresponding to 8~16 m in the prototype), the undrained shear strength of the soil is reduced by about 10% on average after the blasting, and the area can be classified as third-level blasting disturbance zone. Given a range beyond 20cm (equivalent to 16m in the prototype soil), the soil undergoes no disturbance.

4. Conclusion

In this paper, with a seawall project in Huizhou Port as a prototype, based on the blasting similarity theory and through a generalized model and parameter similar design, experimental research on deep silt blasting compaction centrifuge was carried out in a 200g-t centrifuge. The physical and mechanical parameters of the silt soft soil were tested before and after the blasting, and property changes of the soft soil medium were analysed under the explosion to divide the blasting disturbance areas. The test results provide data support for the optimization of the design parameters of the seawall project, and also provide a useful reference for the study on the blasting compaction mechanism of deep silt and similar engineering practices. The following conclusions are mainly drawn.

1) The MDB1 test results show that the explosion impact range of the double-shot detonator is approximately equivalent to 12.0m in the prototype soil. Where: the range of the first-level disturbance zone is 0~4 m; that of the second-level disturbance zone is 4~8 m; that of the third-level disturbance zone is 8~12 m.

2) The MDB2 test results show that the explosion impact range of the three-shot detonator is approximately equivalent to 16 m in the prototype soil. Where: the range of the first-level disturbance zone is 0~4 m; that of the second-level disturbance zone is 4~8m; that of the third-level disturbance zone is 8~16 m.

3) In seawall engineering, blasting compaction is used to treat deep and thick silt. In addition to the advantages of fast construction speed, the rockfill dam formed by blasting displacement can become a part of the foundation, thereby greatly reducing the foundation settlement after construction. At the same
time, it helps to enhance the overall stability of hydraulic structures such as seawall, cofferdam, etc. in deep silt areas.

(4) Based on actual engineering cases, this paper implements centrifuge model test to study the affected area of soft soil disturbance under blasting action, which is a very useful attempt and exploration for the mechanism research and construction method improvement of the soft foundation treatment technology. Due to the limited number of successful test groups, the conclusions on blasting compaction simulation in this study need to be verified by further experimental research.

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