Deformation behavior and damage analysis of underground high-voltage cable duct bank encased by concrete

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Abstract. Due to the shallow burial depth, the concrete duct bank for underground cables frequently encountered differential settlement, tilt and other damage like cracking when construction activity was carried out in the vicinity. This paper briefly presents an experimental study of concrete duct bank with a 1/4 part of real structure under a monotonic static loading, which was put into a soil box in the laboratory. And then numerical simulations were performed for the 1/4 part of real structure and a real-scale concrete duct bank respectively, to investigate the deformation and damage pattern of concrete structure and the wrapped inside conduits. Both the test and numerical results indicated that the failure of concrete duct bank presented a distinct brittle pattern. The mechanical properties of underlying soil play a more dominant role in the bearing capacity, mid-span vertical displacement and mid-span deflection of concrete duct bank. It is proposed that the vertical displacement of concrete duct bank can be set as the monitoring item to reveal its safety state, and the minimum curvature radius of longitudinal deformation profile obtained from vertical settlement at different locations can be computed and be taken as the control index.

1. Introduction
Cable systems are used in addition to the aerial wire network for transmitting electrical energy from different power plants to utility users. In spite of the high initial installation cost in urban areas, underground cable systems play a significant role in the transmission and distribution systems. Concrete duct banks have been used in the cable installations to reduce the external thermal resistance and improve the cable ampacity. The typical configuration of duct bank is presented in Figure 1. In a duct bank, electrical cables are laid out within PVC/MPP/HDPE conduits that are bundled together. These groupings of conduit are often protected by concrete casings. The duct width and height was determined by many factors, such as number of cables, cable system cost, thermal and magnetic field distribution. A lot of work has been done in the geometric design and cable placement of concrete duct bank. For example, El-Kady and Horrocks [1] have put forward an efficient finite element-based technique for calculating geometric factors for extended ranges of the height/width ratio. Zarchi and Vahidi [1] have found the optimal cable placement in a concrete duct bank by finding maximum ampacity and minimum
cable system cost simultaneously. Meanwhile, the thermal and magnetic field optimization in underground power cable duct banks was studied by many researchers [3-5].

Figure 1. Typical configuration of concrete duct bank (2 rows×4 columns)

However, fewer attention has been paid to the structural properties of concrete duct bank. Wang et al. [6] have paid attention to the settlement and damage of working shaft for underground high-voltage electricity cables. Liu et al [7-8] have performed some experimental studies on the concrete cable duct reinforced with glass fiber reinforced polymer bars. Xie et al. [9] has focused on the intelligent sensing of structural deformation of concrete cable duct. In practice, the structural diseases of concrete cable duct, such as differential settlement, tilting and concrete cracking induced by the adjacent construction projects like deep excavation, has been encountered in the soft soil area of Guangdong Province, China.

This paper will firstly give a brief introduction of a laboratory test performed to a 1/4 part of a real concrete duct bank. Secondly, numerical investigation on the structural properties of test specimens and real-scale concrete duct banks, such as loading capacities and damage pattern, has also been performed. Parameter analysis were also conducted in order to explore key factors which may determine the mechanical properties. It aims to provide theoretical basis for the structural safety protection of concrete cable duct.

2. Laboratory Test

2.1 Loading scheme

The test was monotonically loaded by a steel frame with a loading capacity of 2,000kN. In most cases, the concrete duct bank was laid at a depth of 1-3m below the ground surface. Hence, in order to simulate its real surrounding environment, the test specimen was put into a soil box with a dimension of 4.2m×2.7m×2.7m.

Figure 2. The loading scheme of test (units: mm)

To avoid excessive settlement of the concrete duct bank and subsoil which may result in loading difficulty of hydraulic jacks, steel supports was set 200mm below the test specimen. Distributed girds were also used to make a uniformly distributed load on the top surface of concrete duct bank. The
distributed load is equal to the concentrated load $P$ divided by the top surface area. The details can be seen in Figure 2.

2.2 Test Specimen
Two types of specimen as shown in Figure 3 are designed for this test. For the A-type specimen, the section height of concrete is 650mm and the conduits are laid vertically, while B-type is 400mm high and the conduits are laid horizontally. The conduits are made of HDPE (High Density Polyethylene) with 200mm in outside diameter by 10mm in thickness. The compressive strength of concrete $f_{ck}$ in main structure and cushion layer are 21.2MPa and 10.0MPa, respectively; the tensile strength $f_{tk}$ are 2.43MPa and 1.15MPa; the elastic modulus $E_c$ are 25.5GPa, 17.5GPa.

![Figure 3. Test specimen (units: mm)](image)

2.3 Test results
The load-displacement relationship at the midspan of two specimens and the corresponding damage pattern are presented in Figure 4. The maximum load of A-type specimen was 900kPa, while the A-type specimen failed at a load about 400kPa. Nevertheless, the magnitude of mid-span displacements of the two specimen are comparative. The vertical displacement ranges from 60 to 80 mm.

![Figure 4. Load-displacement curve (left) and damage patterns of two specimen (right)](image)

The concrete duct bank was moved out of the soil box after the loading process was finished, which made the visual observation of damage pattern possible. It can be seen that one or two main cracks appeared around the mid span, and the maximum crack width reached to 40mm and 20mm respectively. There are no other small cracks that has been found. Therefore, it can be concluded the failure of
concrete duct bank presented an apparently brittle pattern, which is characterized by one wide and key crack. However, from the perspective of load-displacement curve, the two specimen show no brittle characteristics. This is because the surrounding soil provided the protection to the concrete duct bank, avoiding the sudden breakdown like a simply supported beam. For the B-type specimen, the loading bearing capacity was relatively low, but the mid-span displacement was even a little higher than A-type specimen. This resulted in a distinctly low stiffness of B-type specimen compared with A-type specimen.

3. Numerical Analysis

3.1 Finite element model

The finite element commercial software ABAQUS was used to perform this numerical analysis [10]. The three dimensional numerical models of B-type specimen and real structure were shown in Figure 5. The concrete was modelled with solid element C3D8R with an element length of 0.5 m ~ 1.0 m, while the reinforcement bar was modelled with truss element T3D2.

![Figure 5. The finite element model and boundary conditions of test specimen and real structure](image)

The constitutive model of concrete used in this study was Concrete Damage Plasticity model (CDP) [11-12]. A damage indicator was introduced to reduce the elastic stiffness matrix. When the concrete was uniaxial loaded, two damage indicators \( D_c \) and \( D_t \) are defined to describe the deterioration of elastic stiffness under compression and tension respectively. The stress-strain relationship can be expressed by equations (1) and (2) as below:

\[
\begin{align*}
\sigma &= (1 - d)\bar{\sigma} \\
\bar{\sigma} &= D_0^{pl} (\varepsilon - \varepsilon^{pl}) \\
\dot{\varepsilon}^{pl} &= h(\bar{\sigma}, \bar{\varepsilon}^{pl}) \cdot \dot{\varepsilon}^{pl} \\
\bar{\varepsilon}^{pl} &= \dot{\lambda} \frac{\partial G(\bar{\sigma})}{\partial \bar{\sigma}} \\
D_c &= (1 - d_c)D_0^{el} \\
D_t &= (1 - d_t)D_0^{el}
\end{align*}
\]

where \( \bar{\sigma} \) is the effective stress, while \( \sigma \) is the effective stress when damage is considered and \( d \) is the damage indicator. \( D_0^{el} \) is the initial elastic stiffness matrix without damage, \( \varepsilon \) and \( \varepsilon^{pl} \) represents elastic strain and plastic strain respectively. \( \dot{\varepsilon}^{pl} \), \( \bar{\varepsilon}^{pl} \) and \( \bar{\varepsilon}^{pl} \) is the equivalent plastic strain rate, plastic strain rate and equivalent plastic strain respectively, \( \dot{\lambda} \) is the coefficient of the non-associated flow rule in this plastic material model, while the subscripts \( c \) and \( t \) represent compression, and tension respectively.
The constitutive model of soil used in this study was Drucker-Prager model (D-P). The parameters for material used in this paper were listed in Tables 1 and 2.

### Table 1. Parameters of materials

| Material       | Compressive Strength/MPa | Tension Strength/MPa | Elastic Modulus/GPa | Poisson’s ratio |
|----------------|--------------------------|----------------------|---------------------|-----------------|
| Concrete       | 21.2                     | 2.1                  | 25.5                | 0.2             |
| HDPE conduit   | /                        | 18                   | 0.8                 | 0.4             |

### Table 2 parameters of soil D-P model

| Soil type | Natural weight /kN·m⁻³ | Flow stress ratio k | Friction angle β/° | Compression yield stress σ/y/kPa | Dilation angle Ψ/° | Young’s modulus E/MPa | Poisson ratio μ | Max. plastic strain/10⁻⁴ |
|-----------|-------------------------|---------------------|--------------------|----------------------------------|-------------------|-----------------------|----------------|-------------------------|
| 1         | 18.8                    | 0.91                | 15.9               | 34.4                             | 7.5               | 6.0                   | 0.26           | 3.0                     |
| 2         | 16.7                    | 0.91                | 16.9               | 34.7                             | 8.0               | 4.0                   | 0.32           | 2.0                     |
| 3         | 19.7                    | 0.84                | 30.4               | 39.5                             | 15.0              | 8.0                   | 0.28           | 2.0                     |

### 3.2 Results and discussion

#### 3.2.1 Test specimen

Figure 6 compared the numerical results with the test results for B-Type specimen, in terms of load-displacement curve at mid-span. The maximum load obtained from numerical computation was nearly 400kPa and reasonably well matched with the experimental result. If the applied load at which the key crack extended to a half height of the concrete structure was taken as the loading bearing capacity, the experimental and numerical value was 313.8 kPa and 311.0kPa respectively. At this loading step, the corresponding vertical displacement at mid-span was approximately 54.9mm, and the computed mid-span deflection of concrete duct bank was 12.6mm.

The tension damage of concrete was also shown in Figure 6, which indicated that a crack initiated at the mid-bottom and ran along the height of duct bank. This is in good agreement with what we observed in the test as shown in Figure 4.

![Figure 6. The load-displacement curve and tension damage of concrete for B-type specimen](image)

#### 3.2.2 Parameter analysis

In order to evaluate which factor mainly determines the structural properties of concrete duct bank, parameter analysis was conducted for B-type specimen. In this study, the existence of conduit and the underlying soil type were considered. The parameters for different cases and the computed results with
respect to load bearing capacity, maximum mid-span vertical displacement and deflection in different cases are summarized in Table 3. It is noticed that the deflection of concrete duct bank at mid-span can be computed, according to the vertical displacement at the mid-span subtracted by that at the two-ends.

### Table 3. Computed results of different cases

| Case No. | Existence of conduit | Underlying soil | Loading bearing capacity (kPa) | Max. Mid-span vertical displacement (mm) | Max. Mid-span deflection (mm) |
|----------|----------------------|-----------------|-------------------------------|-----------------------------------------|---------------------------------|
| 1        | Yes                  | Soil type 1     | 311.0                         | 54.9                                    | 12.6                            |
| 2        | No                   | Soil type 1     | 299.0                         | 52.2                                    | 8.2                             |
| 3        | Yes                  | Soil type 2     | 273.4                         | 68.29                                   | 15.86                           |
| 4        | Yes                  | Soil type 3     | 366.8                         | 23.56                                   | 7.24                            |

According to Table 3, the existence of conduits can slightly enhance the loading capacity by 4%, while the deflection increased by 54%. The underlying soil type may play a more dominant role in the structural property of concrete duct. When the concrete duct bank was laid on a poor property soil (Soil type 2), the loading bearing capacity decreased by 12% and the mid-span deflection increased by 26%. If the concrete duct bank was laid on a better property soil (Soil type 3), the loading bearing capacity increased by 18% and the mid-span deflection decreased by 43%. Therefore, it may be concluded that the poorer the soil property, the larger deflection and the lower loading bearing capacity of concrete duct bank will be obtained. Meanwhile, it should be noticed that the variation of mid-span deflection was more remarkable than loading bearing capacity if the underlying soil type changed.

#### 3.2.3 Real structure

The real structure as shown in Figure 1 was simulated as well. Figure 7 shows the tension damage and vertical displacement of this structure. Only one key crack will appeared in the vicinity of mid-span. The damage pattern presents similar law with A-type and B-type specimen.

**Figure 7. The tension damage of concrete (left) and vertical displacement (right) for real structure**

Table 4 summarized the numerical and experimental results of two specimens, and the numerical results of real structures. It can be seen that the loading bearing capacity of real structure and the corresponding mid-span deflection was somewhere in between A-Type and B-type specimen, while the vertical displacement at mid-span was the largest among the three kinds of structure. The large vertical displacement may result from large geometric size and weight of real structure.
Table 4. Computed results of different cases

| Structure type | Height/width ratio | Result type | Loading bearing capacity (kPa) | Max. Mid-span vertical displacement (mm) | Max. Mid-span deflection (mm) |
|----------------|--------------------|-------------|-------------------------------|------------------------------------------|--------------------------------|
| A-type specimen | 650/400 = 1.625    | Test        | 900                          | 57.7                                     | 6.9                            |
| B-type specimen | 400/650 = 0.615    | Test        | 313.8                        | 46.3                                     | 12.2                           |
| Real structure  | 650/1400 = 0.464   | Numerical   | 475.8                        | 61.1                                     | 8.0                            |

Based on the above analysis, it is suggested that vertical displacement of concrete duct bank can be set as the monitoring item to reveal its safety state. At the same time, the mid-span deflection was also a critical index that can reflect the safety state of concrete duct bank. However, the deflection cannot be easily measured as the concrete duct bank was shallowly buried under the ground surface. It is proposed to measure the vertical settlement at different locations and obtain the longitudinal deformation profile. The minimum curvature radius of this profile should be computed and be taken as the control index.

4. Conclusion

A laboratory test conducted on two specimens of underground cable concrete duct bank was presented in this paper. Numerical analysis was performed to the test specimen and real-scale structure. The following conclusions might be concluded:

1. Both the laboratory test and numerical simulation reveal that the failure of concrete duct bank presented an apparently brittle pattern, which is characterized by one wide and key crack.
2. The existence of conduits remarkably enhances the deformation behavior of concrete duct bank. The underlying soil type may play a more dominant role in the deformation behavior and loading bearing capacity of concrete duct bank, and the variation of mid-span deflection was more remarkable than loading bearing capacity if the underlying soil type changed.
3. It is suggested that vertical displacement of concrete duct bank can be set as the monitoring item to reveal its safety state, and the minimum curvature radius of longitudinal deformation profile obtained from vertical settlement at different locations can be computed and be taken as the control index.

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