Settlement and damage analysis of working shaft for underground high-voltage electricity cables

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Abstract. Working shafts or manholes, usually made of concrete or reinforced concrete, are essential parts of the underground electrical power transmission system. However, the working shaft frequently encountered differential settlement, tilt and other damage like cracking when construction activity was carried out near the high-voltage electricity cables. This paper reported a severe damaged working shaft in South China including its settlement and cracks. Numerical simulation was also performed to reveal the evolution of structural damage with an increased differential settlement. The results show a good agreement with field observation in respect to the initiation of concrete tension damage. It is proposed that if a differential settlement higher than 5mm is observed, preventative measures are needed and the risk is conditional acceptable.

1. Introduction

In some metropolitan areas such as London, most electricity is transmitted through underground cables, instead of overhead power lines [1]. Underground cables take up less right-of-way than overhead lines, have lower visibility, and are less affected by bad weather, although the costs of insulated cable and excavation are much higher than overhead construction. Working shafts or manholes, usually made of concrete or reinforced concrete, are essential parts of the underground electrical power transmission system, as they provide space to produce the cable joints in the construction stage, and to maintenance, repair the cables in the future. However, the working shaft frequently encountered differential settlement and damage when construction activity was carried out near the high-voltage electricity cables. This is because these underground cables are traditionally located just beneath the road surface, which leads to a very shallow buried depth of working shaft and makes it a vulnerable underground reinforced concrete structure. Figure 1 shows the construction of working shaft and its typical damage after being put into use.

At the National Grid of South China, safety is the top priority which includes developing and operating safe, reliable and sustainable energy infrastructure. In this context, it is vital to expand our knowledge about the damage pattern and the allowable differential settlement of working shaft for underground cables. Thus, this paper will firstly present a case history of damaged underground cable working shaft induced by adjacent construction activity, and its monitored settlement. Three dimensional numerical model will be then established to investigate the structural damage ant its
evolution process with an increased settlement. It is hoped to be helpful for defining an allowable settlement value of underground cable working shaft.

2. Engineering Background

2.1. The working shaft

The working shaft, defined as “SC13”, is a component of underground electrical power transmission line which links two substations located at Zhuhai, and Macaw respectively. The electricity cables laid in this reinforced concrete structure operate at a voltage of 220kV. The dimensions and reinforcements of this structure were given in Figure 2. The lateral walls and bottom slab of working shaft were cast in place concrete, while the cover plate was precast in factories and removable. The concrete has a strength grade of C30, and the reinforcement bars have a diameter of 14 or 18 millimetres and a strength grade HRB335 (e.g., $f_y = 300$ MPa), according to China's Concrete design code [2]. The bottom slab has a depth of 250mm, while the lateral walls have a depth of 200mm, and the thickness of cover plate is 150mm. The soil layers below the working shaft mainly consist of artificial fill, muddy soil, and silty clay.

2.2. The settlement and damage of working shaft

The severe settlement of working shaft was visually inspected by the patrol stuff of National Grid. The measurement of settlement was performed later at a frequency of approximately 10 days. Four measuring points were set up at the corner of working shaft, as shown in Figure 2. The measuring point 1 was assumed to be the datum point. The measuring results were summarized in Table 1. The maximum settlement was obtained at measuring point 3, with a value up to 380mm at the last observation.
Table 1. Settlement of four measuring points (unit: mm)

| Date | Monitoring points |
|------|-------------------|
|      | 1 (datum point)   | 2           | 3           | 4           |
| 1<sup>st</sup> day | 0                  | -201        | -338        | -89         |
| 12<sup>th</sup> day | 0                  | -223        | -343        | -122        |
| 17<sup>th</sup> day | 0                  | -240        | -350        | -139        |
| 32<sup>nd</sup> day | 0                  | -269        | -365        | -170        |
| 47<sup>th</sup> day | 0                  | -282        | -370        | -193        |
| 59<sup>th</sup> day | 0                  | -305        | -380        | -220        |

A drift ratio was defined as the differential settlement between two corners (also measuring points) divided by the distance of two corners. The evolution of differential settlement along four lines and the corresponding drift ratio was plotted in Figure 3. Obviously a higher drift ratio was found along the short side of working shaft. A maximum drift ratio of 9.5% was obtained along line 1-2 (the short side wall of working shaft), while a maximum drift ratio of 3.5% along line 1-4 (the long side wall of working shaft).

Figure 3. Evolution of measured settlement (unit: mm) and the drift ratio

Severe cracking phenomenon was observed inside the working shaft when several cover plates were removed. Figure 4 presents the cracking mapping along the line 1-2 (see Figures 2 and 3). A main crack with a width at the centimetre level was found near the corner 2. Several slim cracks were also observed along the measuring line 1-2.

Figure 4. The cracking mapping inside the working shaft

3. Numerical analysis

It is a critical issue to estimate how large settlement and drift ratio is allowable for the safety of working shaft. For this purpose, numerical method was employed to analyse the damage status with an increased differential settlement.

3.1. Finite element model

The finite element commercial software ABAQUS was used to perform this numerical analysis. The three dimensional numerical model was 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 (left), boundary and loading conditions (right) of working shaft](image)

The constitutive model of concrete used in this study was Concrete Damage Plasticity model (CDP, for short) [2-3]. 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:

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

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. \(\dot{\varepsilon}^{pl}\), \(\dot{\varepsilon}^{el}\) and \(\varepsilon^{pl}\) is the equivalent plastic strain rate, plastic strain rate and equivalent plastic strain respectively, \(\lambda\) 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 parameters for material used in this paper was listed in Table 2.

In addition, at the bottom surface of working shaft a series of spring element were set up, taking into account the reaction force from the subgrade. The stiffness of spring element was 15Mpa, which was deduced from the subgrade bearing capacity.

Table 2. Parameters of materials

| Material  | Compressive Strength/MPa | Tension Strength/MPa | Elastic Modulus/GPa | Poisson’s ratio |
|-----------|--------------------------|----------------------|--------------------|----------------|
| Concrete  | 22.8                     | 2.3                  | 30                 | 0.2            |
| Steel bar |                           | 335                  | 206                |                |

The boundary and loading conditions in the model was given in Figure 5 as well. The translations in X- and Y-direction of two lateral walls connected by the corner 1 were constrained, and the displacement of corners 2, 3 and 4 (e.g., D2, D3 and D4 as shown in Figure 5) was introduced in a ratio of -305:-380:-220 which corresponds to settlement of measuring points 2, 3 and 4 at the last observation day.

3.2. Results and discussion

The evolution of concrete tension damage and reinforcement bar stress are shown in Figures 6 and 7. It can be seen in Figure 6 that even if the displacement of corner 3 was as small as -1mm, the concrete
around corner 1 was tension damaged with a maximum tensional damage of 0.77. This might contribute to the very strong constraints at the two laterals walls adjacent to corner 1. Fortunately, the stress of reinforcement bar was 51.7MPa, much lower than its yield stress. However, when the displacement of corner 3 increases to 5mm, the stress of reinforced bar around the corner 1 increased sharply to the yield stress 335MPa as shown in Figure 7. In this sense, when a differential displacement with a magnitude of 5 mm was reached, special attention might be paid to this working shaft. In addition, it is very clear that the tension damage initiated at the short side wall along the line 1-2. This is in good agreement with what we observed in the field as shown in Figure 4.

![Figure 6](image1)
Figure 6. The tension damage of concrete (left) and Von-misses stress of reinforcement bar (right) at a corner 3 displacement of -1mm.

![Figure 7](image2)
Figure 7. The tension damage of concrete (left) and Von-misses stress of reinforcement bar (right) at a corner 3 displacement of -5mm.

When the corner 3 displacement increased continuously to -10mm, the tension damage of concrete extended rapidly to the long side wall of working shaft. Unfortunately, the field observation along the long side walls was not available to compare with computation results, as only the worst damaged structural member was recorded by the patrol staff. The computation terminated at a corner 3 displacement of -33mm, while the tension damage of concrete has spread over all the walls at a corner 3 displacement of -20mm as depicted in Figure 8.

If the concept of risk management [4-6] is introduced to safety management of the working shaft for high-voltage electricity cables in the long-term life time, the above results and analysis will provide a strong technical support for the risk level classification of differential settlement for cables' working shaft. More specifically, a differential displacement with a magnitude of 5 mm was proposed to the threshold between the lowest risk level (e.g., IV) and a slightly higher risk level (e.g., III). When a differential settlement higher than 5mm was observed, preventative measures were needed and the risk was conditional acceptable. A differential displacement of 30 mm or 40 mm might be unacceptable, and measures must be taken to lower risk level.
4. Conclusion

The settlement and cracking damage of a working shaft for high-voltage electricity cables were presented in this paper. Numerical simulation was then performed to investigate the evolution of concrete tension damage, in order to broaden our understanding on tolerable differential settlement of the working shaft for cables. The following conclusions might be concluded:

1. A much larger settlement, corresponding to a high drift ratio, was obtained along the short side walls of working shaft, and severe concrete cracking phenomenon was also observed at the same side.

2. The numerical results show the concrete tension damage initiated at the short side wall with a largest settlement, which is in good agreement with what we observed in the field.

3. It is proposed that if a differential settlement higher than 5mm of working shaft is observed, preventative measures are needed and the risk is conditional acceptable.

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