論文 / 著書情報
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Authors	N. Chijiwa, H. T. Mai, M. Iwanami
Citation	Proceedings of the 7th Regional Symposium on Infrastructure Development, Vol. 20, No. 7, pp. 80-83
Pub. date	2015, 11

Rapid Deterioration of the Anchor Performance of the Wind Turbine Caused by Liquid Water

N. Chijiwa
Tokyo Insitute of Technology, Tokyo, Japan, chijiwa@cv.titech.ac.jp,

H. T. Mai
Shimizu Corporation, Tokyo, Japan, mai.thihong@shimz.co.jp,

M. Iwanami
Tokyo Insitute of Technology, Tokyo, Japan, chijiwa@cv.titech.ac.jp

Abstract

In some wind turbines, it is found that sludge spouting on the tower foundation and the tower is lifted up just after several months have passed from starting service. Common characteristic of those wind turbine towers is that they are anchored to the foundation by anchor ring method. In anchor ring method, ring-shaped base plate welded to the wind turbine tower is expected to act as anchor in the foundation. It is suspected that liquid water may have some effect on such a kind of the anchor system. In this research, the experiments with concrete foundation model is carried out to clarify the mechanism of deterioration of the anchoring performance. The influence of the liquid water, bond between foundation concrete and turbine tower, pore-distribution of foundation concrete, and loading speed on the anchoring performance under cyclic loading is investigated. After liquid water ingresses to the foundation through the interface between foundation concrete and turbine tower, the anchoring performance is rapidly deteriorated. Even when the bond between foundation concrete and turbine tower is originally sound, liquid water can ingress to the foundation, and rapid deterioration is caused. Because the pore distribution of the foundation concrete and the loading speed have some influence on the deterioration process, it is concluded that the viscous character of the liquid water acts important role on this deterioration process. Under the existence of water, deterioration is accelerated by water wedge effect, erosion with crushed particle, and cavitation erosion. The flow of water has also act important role on the deterioration process because it keeps undamaged concrete surface of the foundation concrete directly contacting to the anchor plate. Based on the knowledge on the deterioration process, rational countermeasures on design and maintenance are proposed.

1. Introduction

Wind power is drawing attention as a renewable source of energy and the number of wind power installations is increasing. One of the wind turbine tower fixing methods is the anchoring method, which welds a base plate to the steel tower and embeds it inside the concrete foundation (Figure 1). Sludge consisting of fine powder and water is ejected from the interface between the steel anchoring and the concrete of the foundation fixed in place by this anchoring method, causing the tower to be lifted up and in some cases necessitating repair work just a few months after commencement of service. The bearing stress applied as the result of the wind turbine operation is sufficiently low in relation to the concrete strength that such rate of degradation of concrete is unlikely in typical environments. In view of the fact that sludge, which is a mixture of water and powder, is ejected, the presence of liquid water is surmised to induce the rapid deterioration of concrete.

A previous study reported that repetitive load application in the presence of liquid water significantly shortens fatigue life[1]. The causal mechanisms have been variously identified as reduction in compressive strength due to changes in surface energy[2], washout effect of cracked surface[3], the wedge effect[4], and cavitation[5], among other things, yet the influence of water on anchorage performance cannot be said to have been fully elucidated. A case similar to the damage discussed here was reported by Matsuda in a study on the areas around bridge supports degrading into a mud pumping state and the estimation of the mechanism at work[6], but that study stopped short of the quantitative analysis required for actual design and operation taking into account the influence of the above on structural performance deterioration.

In view of the above, the present study was designed to determine through experiments the causal mechanism of the damage observed this time in the wind turbine foundation anchoring area, gain a qualitative grasp of the influence of water on concrete anchorage performance, and propose effective measures.

2. Experimental design

Specimens were designed to simulate the anchorage part of an anchor-ring method type wind turbine foundation. The specimen was fixed to a frame with four PC steel rods. Each PC steel rod was pre-stressed to about 150 kN. W/C ratio of the casted concrete was 62.4 %. The maximum aggregate size was 13 mm. A water tank was fabricated over the specimen so as to surround the steel, and water was poured there to simulate pooled rainwater. Further, in Case 1 and Case 2, a 5 mm thick sheet of expanded polystyrene was embedded directly under the anchor plate to foster relative slippage between the steel and concrete and cancel the interfacial bond. Case 3 does not have such an artificial defect to simulate real situation.

The compressive strengths of the concrete at 28 days were 29.0 N/mm^2 for Case 1, 34.0 N/mm^2 for Case 2 and 34.0 N/mm^2 for Case 3. The bearing strength ratio in actual wind turbines is 0.19 at the rating (during normal service), and 0.43 at the cutout wind speed where power generation is stopped for risk prevention. The experiment was designed so that the pull-out design strength of the specimens would approximate the bearing strength ratio of 4, and the peak of alternating cyclic push-pull loading was set to the bearing strength ratio of 0.43, which is equivalent to the wind turbine cutout load (load at which the operation is stopped to protect the equipment). Bearing in mind the figure of 0.35 Hz, which is the frequency measured for the actual structure, 0.5 Hz was set as the basic value for the loading rate during cyclic loading.

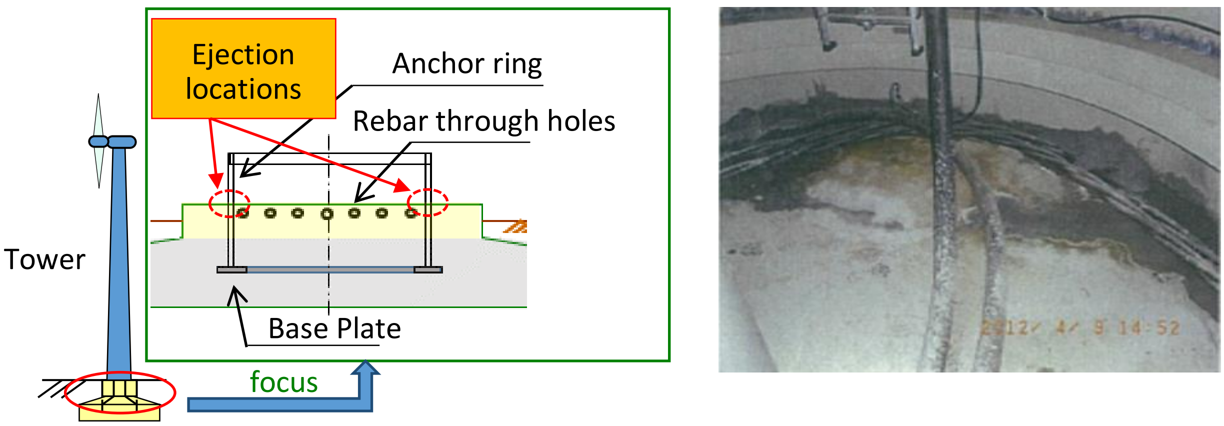

Figure 1: Anchorage zone and sludge ejection locations.

3. Experimental Results and Discussion

(1) Influence of the presence of liquid water on anchorage performance

Cyclic loading was performed according to the compressive strength of concrete, under the conditions of positive and negative loads of 30 kN with water supplied in Case 1, and positive and negative loads of 35 kN with no water supplied in Case 2. The maximum and minimum displacements per cycle for Case 1 and Case 2 are plotted in Figure 2.

In Case 2 without water supplied, in the interval from 10,000 repetitions to 200,000 repetitions, pull displacement was 0.12 mm, and push displacement 5.02 mm, with almost no change in displacement. Likely on account of the push displacement being equivalent to the compression of the expanded polystyrene under the plate, damage to the specimen was extremely small and did not lead to breakdown of the specimen.

On the other hand, in Case 1 where water was supplied, water was confirmed to reach the bottom flange of anchor at 35,000 cycles. Thereafter, after the entire anchor plate showed signs of sinking down toward the interior, pull displacement suddenly surged up to 7.1 mm and push displacement became 6.1 mm. At the same time, sludge began spewing forth from the steel interface to the top surface of the specimen, being gradually accumulated. This sludge ejection situation resembled very closely observed at actual wind turbines. Thereafter, pull displacement continued to increase, with the load control capability of the actuator unable to keep up, and as it became impossible to transmit the 30 kN load to the concrete, the loading rate was lowered to 0.25 Hz, 0.1 Hz, 0.075 Hz according to the displacement increases in order to ensure reliable application of the set load.

As a result, when the amplitude of 30 kN was reliably applied continuously to the concrete, total displacement reached 100 mm or more at approximately 50,000 loading cycles. Following several additional thousand loading cycles, the experiment was concluded, the specimen was sectioned and its inside was inspected, revealing that a cavity almost the width of the anchor plate and 120 mm long in the pull direction and 10 mm long in the push direction had formed inside the specimen. Observation of the sides of that cavity showed a state as if about 0.5 mm of the cement paste part had been scooped out, leaving behind the coarse aggregate. Examination by a heavy liquid analysis of the composition of the ejected sludge at the top of the specimen indicated the composition of the fines to be consistent with the original concrete mix proportion, and it was found that not only the cement paste, but even the aggregate, had been finely ground.

These results indicate that when liquid water ingresses the concrete all the way to the area around the anchor plate, progression of the damage in the interior of the concrete is accelerated and pull action occurs significantly faster than under dry conditions.

(2) Influence of steel-concrete interface bond on liquid water ingress

In Case 1, which as described earlier features the placement of expanded polystyrene directly under the anchor plate, allowing easy sinking of the plate, the interfacial bond between the steel and concrete is easily broken. By contrast, the anchor plate in Case 3 is in direct contact with the concrete, so that the interfacial bond is relatively difficult to break. Whereas in Case 1, water entered the tube at 35,000 cycles, in Case 3, this occurred at 95,000 repetitions (Figure 3).

The results of this experiment are considered to show that even if concrete is compacted densely around steel, the ingress of water is difficult to avoid. When tensile force is applied to steel, gaps occur between the concrete and the surrounding concrete owing to the Poisson effect. When water pools, ingress of liquid water through gaps occurs. Next, when compressive force is exerted, the steel deforms, pushing outward the concrete around it, so that part of the liquid water that has ingressed is ejected, while part is pushed further inside, penetrating the pores of the concrete at the interface and promoting reduction of the interfacial bond through the wedge effect. The deformation of the steel increases and gaps are created around the anchor, after which the anchor starts moving up and down like a piston, causing liquid water to be drawn in from outside and then ejected, which is thought to, along with accelerating sludge discharge, exacerbate the deterioration mechanism associated with the viscosity of water, for example wedge effect, erosion and cavitation. In the actual structure, it is possible that water ingress may be further promoted by reduction of the interfacial bond between the steel and concrete by the effect of bleeding at the bottom and sides of the steel plate and also shrinkage of the concrete.

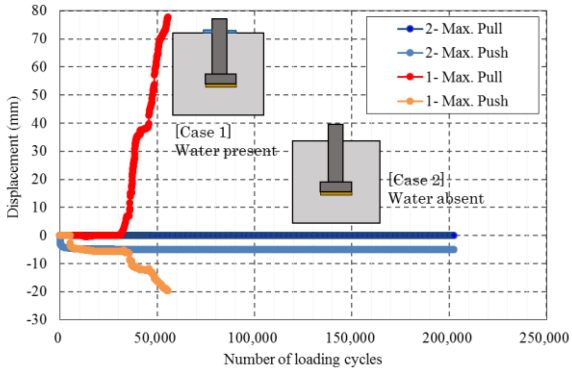

Figure 2: Effect of water presence.

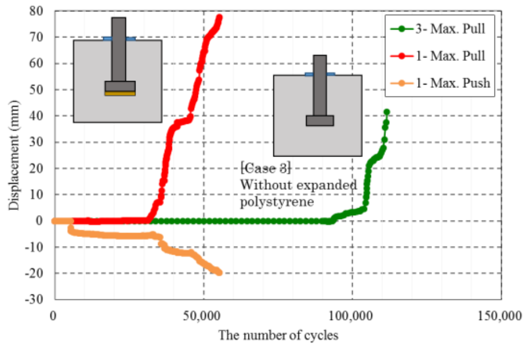

Figure 3: Effect of bond soundness.

4. Conclusions

The following conclusions can be drawn from this study.

1) In environments where liquid water is present in the support area of the anchorage zone and where cyclic loading is applied, the anchorage performance of the steel-concrete composite structure is remarkably lower than that assumed for dry conditions.
2) Even when the steel-concrete bond is sound, subjection to repeated push and pull load makes liquid water ingress from the interface possible.

5. References

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