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Scientific paper

Rapid Degradation of Concrete Anchorage Performance by Liquid Water

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Abstract

Sludge ejection from the foundation of a wind turbine tower fixed by the anchor-ring method and the resulting sludge buildup have been confirmed to cause the undesirable phenomenon of lifting of the tower. Using specimen that is a partial model of the wind turbine foundation, this study investigates the influence of liquid water, differences in W/C, and differences in loading speed, to analyze developing factors on the concrete damage . The results shows that penetration of liquid water from rainfall and snowfall produces a wedge effect, breakdown of the concrete pore skeleton structure, grinding by sludge particle, cavitation and other effects, and leads to rapid deterioration of the anchorage performance of concrete foundation. Based on the knowledge on the deterioration process, rational countermeasures on design and maintenance are proposed.

1. Introduction

Wind power is drawing attention as one of renewable energy sources and the number of wind power installations is increasing. One of the wind turbine tower fixing methods is the anchor-ring method, which welds a base plate to the steel tower and embeds it inside the concrete foundation (**Fig. 1**). Sludge consisting of a mixture of fine powders and water is ejected from the interface between the steel anchor-ring and the concrete foundation fixed in place by this anchor-ring method, causing the tower to be lifted up. And also in some cases that repair work had been taken just a few months after the commencement of service have been reported (**Fig. 2**). The bearing strength 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 powders, is ejected, the presence of liquid water is surmised to induce the rapid degradation of concrete.

A previous study reported that repetitive load application under the presence of liquid water significantly shortens fatigue life (Matsui 1987). The causal mechanisms have been variously identified as reduction in compressive strength due to changes in surface energy (Gilkey 1926; Matsushita 1984; Matsushita and Onoue 2006), the cracked surface washout effect (Gebreyouhannes *et al.* 2008), the wedge effect (Slowik and Saouma 2000), and cavitation (Maekawa and Fujiyama 2013), among other things, yet the influence of water on this anchorage performance has not been fully elucidated. A case similar to the damage discussed here was reported by Matsuda in a study on the concrete around bridge supports degrading into a mud pumping state and the estimation of the mechanism (Matsuda 2013), but that study have gone no futher the shortening the quantitative analysis required for the actual design and operation taking into account the influence of the above on structural performance deterioration.

In view of the above, the present study have elusidated the causal mechanism of the observed damage at this time in the wind turbine foundation, gain a qualitative grasp of the influence of water on concrete anchorage performance, and propose effective measures.

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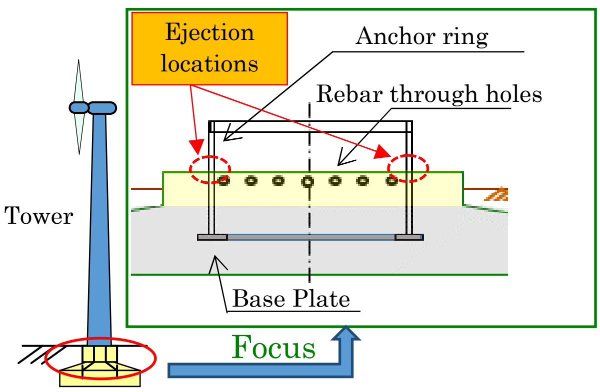
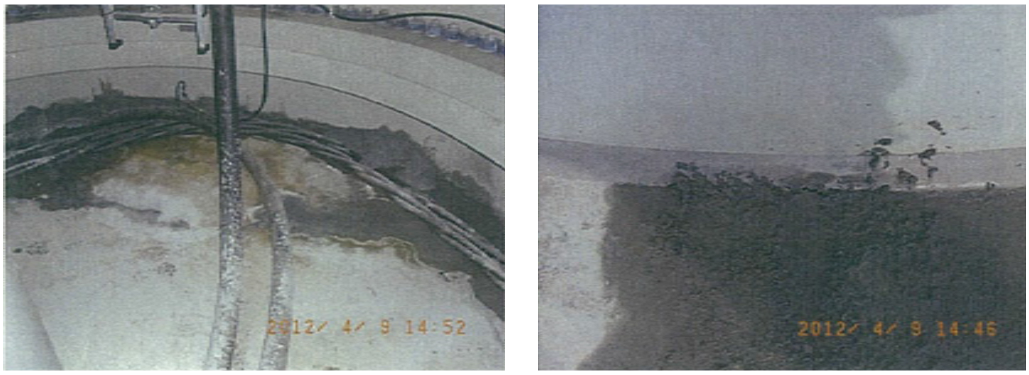


Fig. 1 Anchorage zone and sludge ejection locations.



a) Ejection situation inside tower b) Ejected sludge

Fig. 2 Sludge ejection situation.

2. Experimental design

(1) Estimation of damage causing factors

Based on existing knowledge, the influencing factors were estimated and the experiment conditions narrowed down. The ingress path of water into the foundation is considered to be the interface between the steel anchor-ring and the concrete, and a preceding significant decrease in adhesion may be the cause of liquid water ingress. Possible sludge formation and damage development causes are the wedge effect of water that enters inside the foundation on fine cracks and micro-pores in concrete, cavitation erosion resulting from instantaneous water pressure decreases caused by rapid vertical movement of the base plate due to the viscous nature of water, and also grinding of the concrete surface in the process of water-borne advection of particles generated from the crushing of micro-pores. Therefore, the major influencing factors of concrete damage development were surmised to be interfacial bond degradation, the presence of liquid water, the pore structure of concrete, and the loading rate.

(2) Experiment cases and objectives

To investigate the effect of the influencing factors surmised in section (1) on structural performance, five cases, as detailed in **Table 1**, were set. First, Cases 1 and 2 were compared to determine the effect of the presence or absence of liquid water on the anchorage performance of concrete. Then, Cases 1 and 3 were compared to determine to which extent the chemical bond at the steel-concrete interface influences the water flow rate. Next, Cases 3 and 4 were compared to assess the degree of influence of differences in pore structure of concrete on the damage progress and on the wedge effect of water to accelerate the damage. Finally, the influence of crack development as the result of the wedge effect, cavitation erosion, and grinding by sludge particle was assessed along with clarification of the influence of the loading rate on fatigue life, based on the difference in loading rate between Cases 3 and 5.

(3) Specimen specifications

The specimens, which modeled part of an anchor-ring method type wind turbine foundation, consisted of a cube with 500-mm sides containing steel representing the anchor-ring at its center (**Fig. 3**). **Table 2** lists the mix proportions of the concrete that was used. The maximum aggregate size was 13 mm. To verify that water penetrated into the specimen, a tube with outer diameter of φ 6 mm reaching the top surface of the plate was placed, and in some of the specimens, a plastic tube

Table 1 Specimen cases.

	No. 1	No. 2	No. 3	No. 4	No. 5
Loading method	Cyclic				
Water supply	Yes	No	Yes		
W/C (%)	62.4	62.4	62.4	40.9	62.4
Loading rate (Hz)	0.5	0.5	0.5	0.5	0.1
Compressive strength of concrete at 28 days (N/mm^2) (=Bearing strength)	29.0	34.0	34.0	51.0	31.0
Simulated void by putting an expanded polystyrene sheet under base plate	Yes	Yes	No	No	

Table 2 Mix proportions of concrete.

Water-cement ratio (%)	Sand-total aggregate ratio (%)	Unit content (kg/m^3)				
		Cement	Water	Fine aggregate	Coarse aggregate	AE water reducing agent
62.4	53.9	313	195	935	824	3.91
40.9	51.0	428	175	865	853	4.71

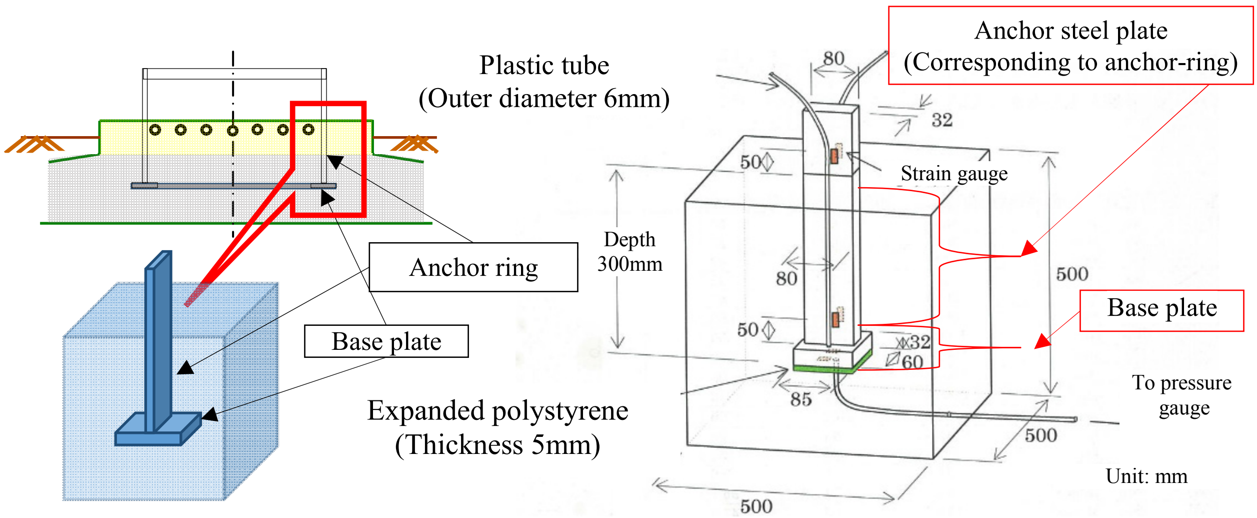


Fig. 3 Shape and dimensions of specimens.

for measuring the water pressure under the base plate was also placed. 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 Specimen No. 1 and Specimen No. 2, a 5-mm thick sheet of expanded polystyrene was embedded directly under the base plate to foster relative slippage between the steel and concrete and cancel the interfacial bond. The W/C of the basic specimens was somewhat higher than that of the actual foundation, in order to facilitate the ingress of water into micro-pores and accentuate the effect of their breakdown. For Case 4, the W/C was decreased significantly for the purpose of further clarifying the effect of suppressing the ingress of water into micro-pores.

(4) Specimen setting conditions and measuring points

Loading was done with the anchor steel plate and actuator connected with a special jig as shown in **Fig. 4**. Further, the specimen was fixed to a frame with four PC steel rods. Each PC steel rod was prestressed to about 150 kN.

Gauges for measuring the strain in the anchor steel plate (corresponding to the anchor ring part in a real tower) were attached at four locations on the vertical plane to match the loading direction, and an additional two strain gauges were attached to the underside of the base plate. Displacement transducers were installed on the upper surface of the concrete in order to measure vertical displacement at the measurement points set on the side of anchor steel plate approximately 10 cm from the upper surface of the concrete.

(5) Cyclic loading level and rate

The compressive strengths of the concrete of each specimen at 28 days are listed in **Table 2**. 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 pre-

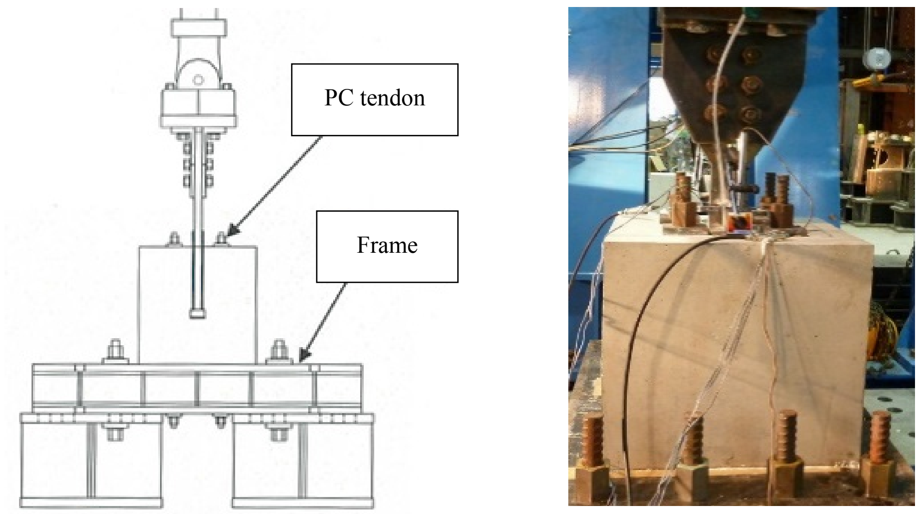


Fig. 4 Installation condition of specimens.

vention. The peak of alternating cyclic loading was set to the bearing strength ratio of 0.43, which is equivalent to the wind turbine cutout load.

The results of a monotonic test conducted using Specimen No. 1 with W/C of 62.4% are shown in **Fig. 5**. In this test, the specimen was pushed down 5 mm, equivalent to the thickness of the expanded polystyrene, and the pull-out test was then performed. Based on the results of this test, the chemical bond between the steel and concrete broke under load action in the range of 20 kN to 30 kN for both pushing and pulling. When the pull displacement reached 5.1 mm, cracks appeared and load started decreasing. The pull peak load was 443 kN. The load equivalent to the bearing strength ratio of 0.43 used in the cyclic loading test for the material strength of the specimen is estimated at 31 kN, but this is a load equivalent to just about 6% of the obtained pull peak load.

Bearing in mind the figure of 0.35 Hz, which is the frequency measured for the actual wind turbine tower, 0.5 Hz was set as the basic value for the loading rate during cyclic loading. For Case No. 5 only, loading using 0.1 Hz, a value lower than 0.35 Hz, was performed to clarify the influence of the loading rate on fatigue life.

3. Experiment 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 without water supplied in Case 2. The maximum and minimum displacements per cycle for Case 1 and Case 2 are plotted in **Fig. 6**.

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 base 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 be moving inside the tube at 35,000 cycles. Thereafter, after the entire base 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 anchor steel plate inter-

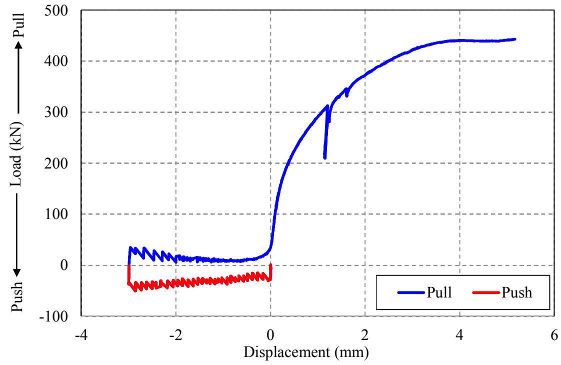


Fig. 5 Static push and pull test results.

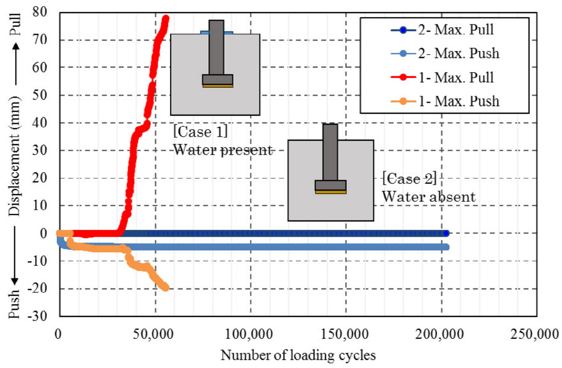
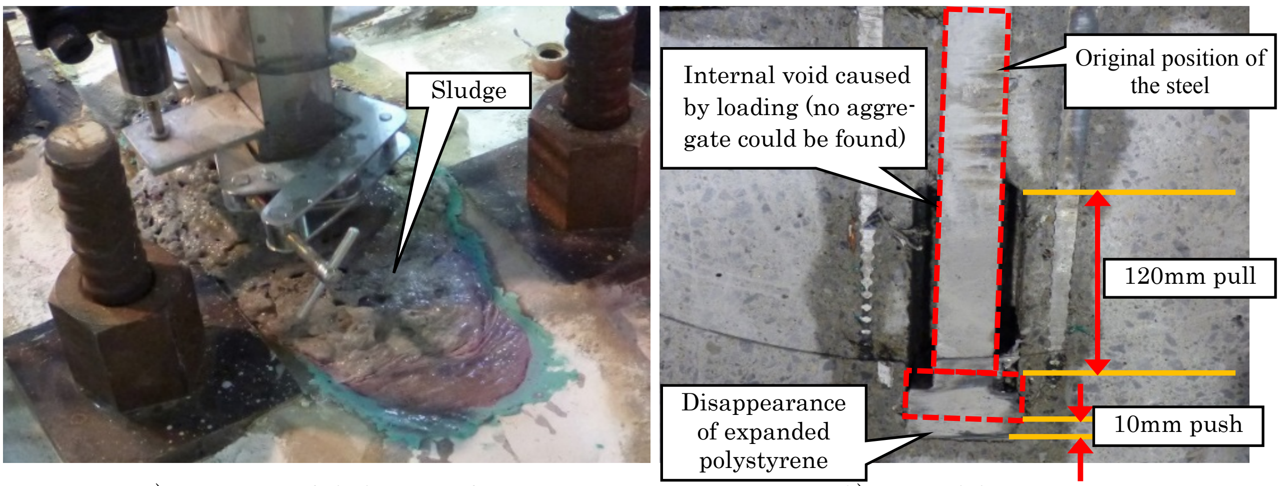


Fig. 6 Influence of presence of liquid water on anchorage performance.



a) Deposition of sludge at surface b) Internal damage

Fig. 7 Concrete damage state.

face to the upper surface of the specimen, where is gradually accumulated (**Fig. 7a**). This sludge ejection situation very closely resembled that 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, and 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 loading experiment was stopped and the specimen was sectioned and its inside was inspected. It was revealed that a cavity almost the width of the base plate and 120 mm high in the pull direction and 10 mm high in the push direction had formed inside the specimen (**Fig. 7b**). On the sides of that cavity, about 0.5 mm of the cement paste part had been scooped out, leaving behind the coarse aggregate. Examination by a heavy liquid analysis on the composition of the ejected sludge at the top of the specimen indicated the composition of the fines to be consistent with the formulation of the concrete used in the experiment, 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 to the area around the base plate, progression of the damage in the interior of the concrete is accelerated and the anchorage performance is deteriorated 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 base plate, allowing easy sinking of the plate, the interfacial bond between the steel and concrete is easily broken. By contrast, the base 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 (**Fig. 8**). It should be noted that distinctive motion was observed, with only the pull displacement of the base plate temporarily becoming smaller around the time of water ingress, and following overall sinking action, pull displacement gradually increasing (**Fig. 9**).

The results of this experiment are considered to show that even if concrete is compacted well around anchor steel plate, 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. After the displacement of the base plate increases and gaps to be a path of liquid water are created around the anchor steel plate, the base plate starts moving up and down like a piston, causing liquid water to be drawn in from outside and then ejected. Along with accelerating sludge discharge, the base plate starts to contact directly to the newly appeared undamaged internal concrete surface continuously, and crush them in the same process. As the displacement becomes large, the amount of moving water is also increased, and degradation mechanism associated with the viscosity of water (e.g. grinding by sludge particles and cavitation erosion) can be induced. In the real structure, it is possible that water ingress may be further promoted by the reduction of the interfacial bond between the anchor steel members (=anchor steel plate and base plate) and concrete caused by bleeding and shrinkage of the concrete.

(3) Relationship between pore structure and reduction of anchorage performance by liquid water

Cyclic loading was performed using different loads according to the compressive strength of concrete to keep the ratio of the bearing strength as 0.43, namely positive

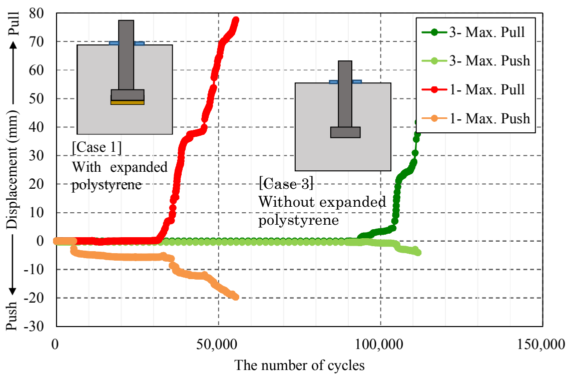


Fig. 8 Relationship between reduction of interfacial bond and accompanying reduction of anchorage performance.

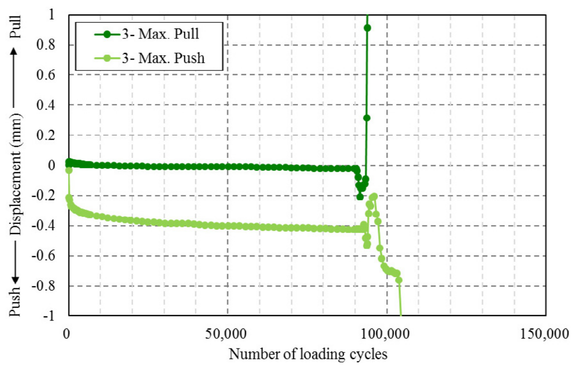


Fig. 9 Characteristic displacement before pull acceleration (Case 3 example).

and negative loads of 35 kN for Case 3 and positive and negative loads of 51 kN for Case 4, with water supplied in both cases. **Fig. 10** shows the maximum and minimum displacements per cycle plotted against the number of repetitions.

In Case 3 using a high W/C, water was observed to enter the tube in the vicinity of 95,000 repetitions. Immediately after that, both pull displacement and push displacement increased sharply. At about 105,000 repetitions, pull displacement reached about 10 mm, and push displacement 1.2 mm. Sludge was ejected on the upper surface, where it gradually accumulated. On the other hand, in Case 4 with a low W/C, water movement inside the tube was detected when the number of repetitions reached 220,000. However, even after water entered the tube, displacement did not increase, and it began changing gradually from 280,000 repetitions. The change, rather than sharp, was a gentle increase and after about 360,000 repetitions, pull displacement reached 5 mm. Sludge was deposited on the upper surface of the specimen (**Fig. 11**). Until the number of repetitions reached about 500,000, the mean position of base plate was shifted to tension side. This is because the concrete strengthen was high, the path to discharge the sludge to outside was hard to form and the sludge was deposited under the base plate.

Based on these results, the rate of progress of breakdown by liquid water was different when using concrete with a low W/C, which had long fatigue life than concrete with a high W/C.

(4) Relationship between loading rate and decreasing anchorage performance in the presence of liquid water

To analyze the influence of the viscous behavior of liquid water on the progress of breakdown, loading was performed at the rate of 0.1 Hz in Case 5 and the results were compared with Case 3, which used the loading rate of 0.5 Hz. **Fig. 12** shows the maximum and minimum displacements per cycle plotted against the number of repetitions. It should be noted that to unify the bearing strength ratio with other experiments, loading in Case 5 was performed using positive and negative loads of 30 kN.

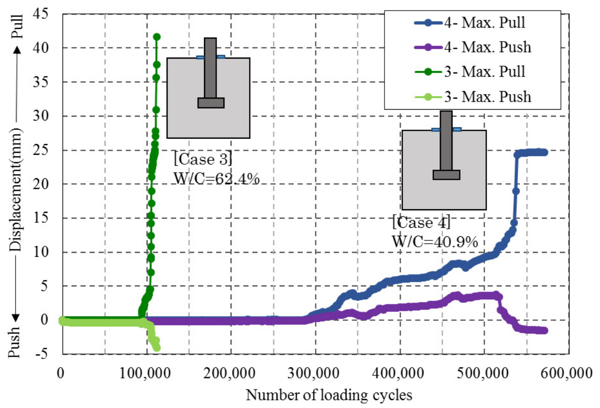


Fig. 10 Relationship between pore structure and reduction of anchorage performance by liquid water.

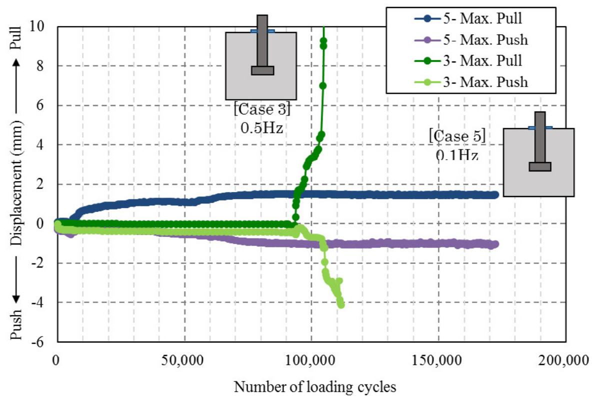


Fig. 12 Relationship between loading rate and reduction of anchorage performance by liquid water.

Specimen 3, upper surface Specimen 4, upper surface

Fig. 11 Sludge deposition state after test.

In Case 3, which uses a higher loading rate, displacement grew more sharply following water ingress in the vicinity of 95,000 repetitions, leading to earlier breakdown. On the other hand, in Case 5 with a lower loading rate, water entered the tube at 8,000 repetitions, and then displacement gradually increased, but at 80,000 repetitions, pull displacement was just on the order of 1.5 mm and push displacement about 1.0 mm, and thereafter displacement remained unchanged and breakdown did not occur even after 170,000 cycles.

Observation of the movement of the water head inside the tube after water entered the tube showed that in Case 5 with loading rate of 0.1 Hz, the next operation started after the position of the water head stabilized at a given push-pull location, whereas in Case 3 with loading rate of 0.5 Hz, the next operation started without the position of the water head first becoming stable. Whereas in Case 5, there was sufficient time for water pressure to be statically balanced with the surrounding environment, in Case 3, the water head was observed to keep moving under pressure without reaching statically balanced state with the surrounding environment, which is considered to have had a major influence on the progress of breakdown.

As shown in **Fig. 13**, it is known that the higher the loading rate during fatigue loading under dry conditions, the larger the number of repetitions until breakdown is (Ishibashi *et al.* 1987). However, when water has ingressed the concrete, the number of repetitions until breakdown is believed to be low to the extent that the loading rate is high.

4. Discussion of acceleration mechanism of concrete damage by liquid water based on microscopic mechanism

(1) Promotion of breakdown by the wedge effect

The results of Case 3 and Case 4 in which differences in pore structure were observed, and the results of Case 3 and Case 5 in which differences in loading speed were observed, suggest that in the presence of liquid water, a wedge effect from the viscous nature of the water occurs in micro pores and fine cracks, promoting breakdown of the structure of the hardened cement paste (**Fig. 14**).

Voids of various diameters are present in concrete. Owing to the viscous nature of liquid water, water pene-

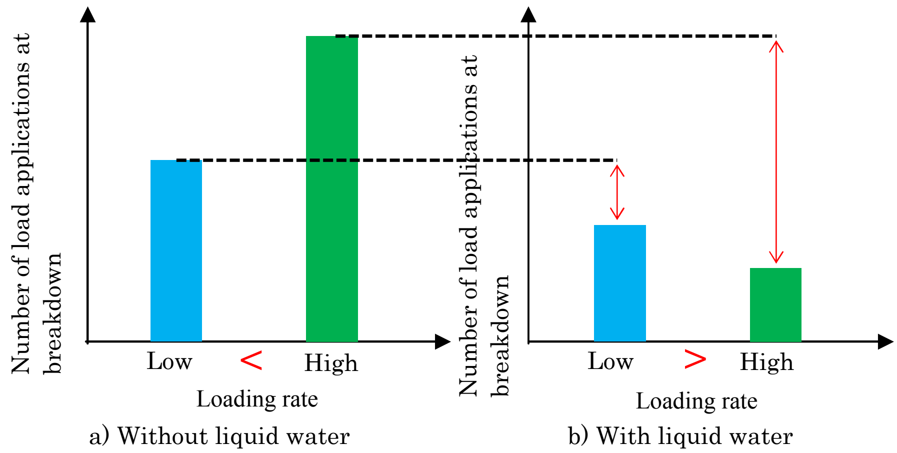


Fig. 13 Influence of loading rate in presence of liquid water.

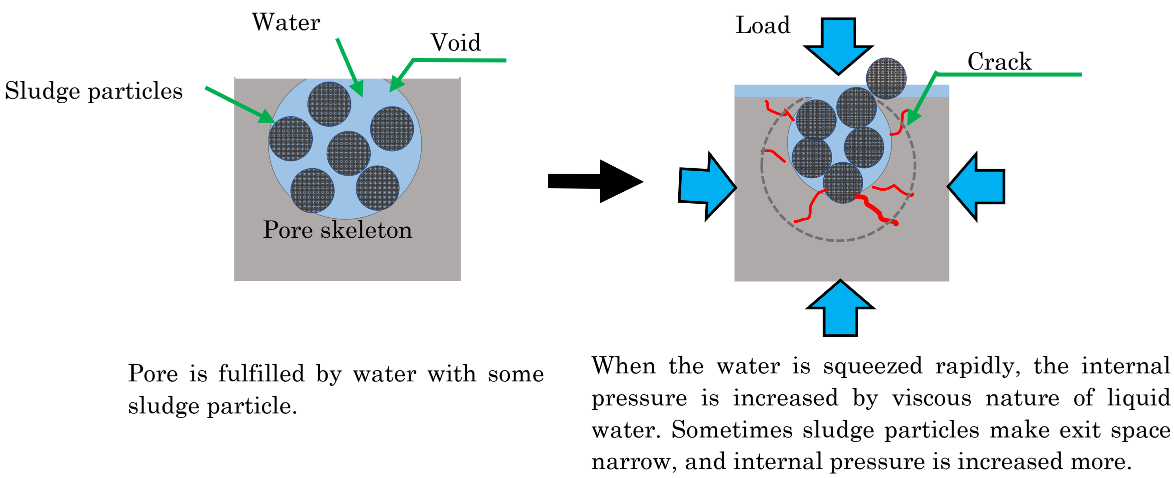


Fig. 14 Structure breakdown by wedge effect.

trates easily through large pores, but is less likely to penetrate through fine pores. If the W/C is decreased, the hardened cement paste becomes denser, and the volumetric ratio of finer pores will be larger. The strength of the concrete is also increased, and it will be more durable to other additional effect caused by the movement of viscous liquid (e.g. grinding by sludge particles and cavitation erosion). This is considered to be the cause behind the differences between Case 3 with W/C of 62.4% and Case 4 with W/C of 40.9%. In Case 4 with W/C of 40.9%, the facts that ingress of liquid water was more difficult owing to the larger number of fine pores and that the wedge effect did not easily develop are considered to be why the life reduction rate was restrained. Voids caused in concrete as the result of entrained air are larger than capillary pores by 1 to 2 orders of magnitude. Based on the fact that water easily ingresses such air entrained voids but also easily egresses them, such voids are not considered to be significantly involved in the progress of breakdown by the wedge effect.

The wedge effect in micro-pores and fine cracks originating from the viscosity of liquid water, the effect of viscosity is suppressed to the extent that the moving speed of liquid water is low, making the wedge effect difficult to achieve. The results of Case 3 and Case 5 are considered to manifest this. Case 5 with low loading rate had faster water ingress than Case 3, and this is consistent with the fact that lower loading rates result in a lower number of repetitions until breakdown (Ishibashi *et al*. 1987) per existing knowledge with regard to the condition where there is no liquid water action. However, following water ingress, promotion of breakdown by the wedge effect is observable, and this is considered to be the cause why, in Case 3 where this effect is more pronounced, breakdown occurred faster.

(2) Promotion of breakdown by continuous exposure of intact surfaces as result of the transport of fine fragments by water

In the vicinity of the base plate, mechanical action such as bearing stress and the aforementioned wedge effect causes breakdown of the concrete as the result of which fine fragments are produced. When water is not present, the fine fragments remain in their original location and serve as a cushion protecting intact surfaces. However, when liquid water is present and water advection occurs, fine fragments are transported away from their original location to other locations as the result of liquid water advection, and new intact surfaces are constantly exposed to the mechanical action from the base plate. The decrease of shear transfer through washout has already been pointed out in another study (Gebreyouhannes *et al*. 2008), and a similar mechanism is considered to be at work in the present experiment, promoting breakdown.

Further, in the present experiment, there is a certain interval of time from the ingress of water until sludge ejection, and prior to the rapid increase of pull displacement and sludge ejection, the entire base plate was observed to temporarily sink inside in all cases (**Fig. 9**).

From these experimental results, the mechanism of water movement path formation around the base plate is inferred as shown in **Fig. 15**. First, under the wedge effect, the concrete over the base plate breaks and spalls, and the resulting fragments are transported in water and become lodged between the upper surface of the base

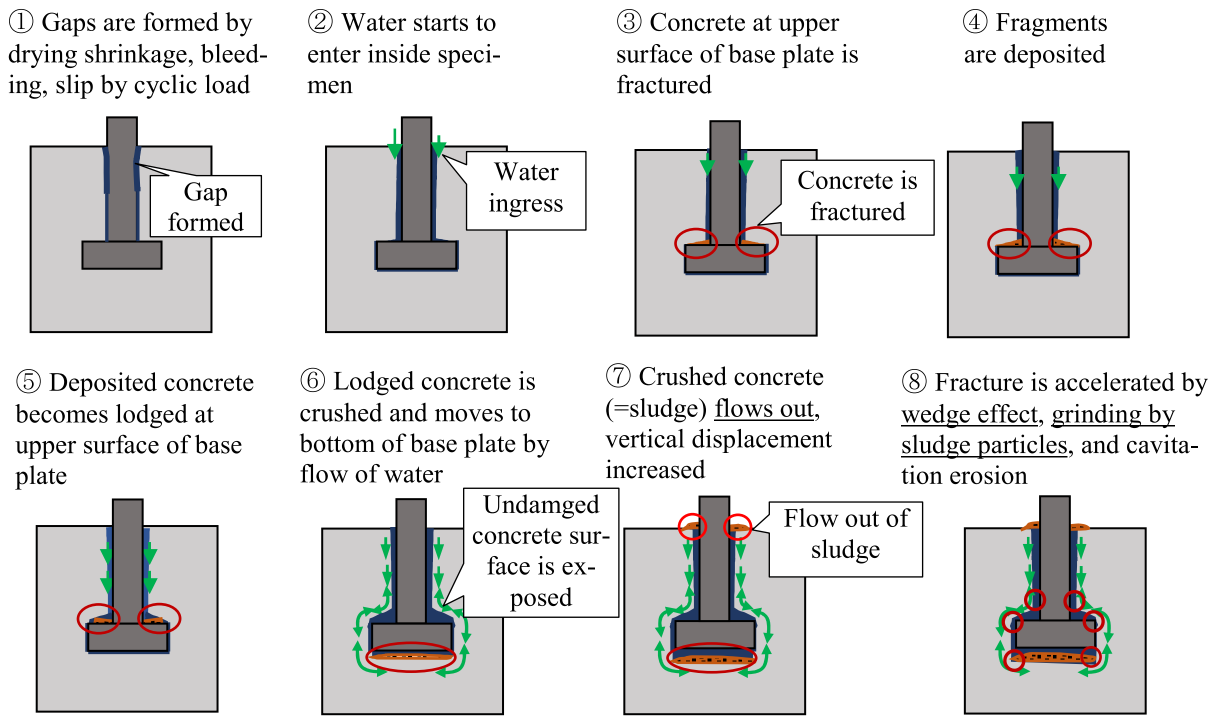


Fig. 15 Breakdown development mechanism around anchor.

plate and the concrete, causing the entire base plate to temporarily sink. The lodged fragments are crushed by cyclic loading and are then gradually transported under the base plate via the water movement path formed around the base plate, and the upper surface of the base plate comes into direct contact with intact concrete and causes that concrete to break down. As the displacement width of the base plate gradually grows larger, the bond of the base plate sides decreases, and sludge movement paths are formed from the internal voids around the base plate to the water tank on top of the specimen, so that sludge generated internally is ejected to the outside, the base plate comes into direct contact with the concrete, subsequently causing a rapid increase in pull displacement.

(3) Other breakdown factors
The used specimens were sectioned and the walls of the internal voids generated by loading were examined, revealing that about 1 cm to 2 cm of the cement paste part had been scooped out, leaving behind the aggregate. This is thought to have been caused by advection of liquid water containing solid particles inside the specimens, with the particles causing erosion (Graham *et al.* 1987) by colliding with the walls during that process, as well as cavitation erosion (Maekawa and Fujiyama 2013; Momber 2000) through the internally generated negative pressure. Liquid water is involved in these effects, which are all phenomena originating from the mechanical response of the porous structure of concrete, and further study in the future to quantitatively analyze their respective impacts is considered necessary.

5. Verification using actual structure and design and construction measures

(1) Re-analysis of actual structure degradation case
Based on the knowledge obtained from this study, the relationship between lifting of the tower and the water-cement ratio listed in the mix design and the weather conditions was analyzed for existing wind turbine foundations fixed by the anchor-ring method. The results are shown in **Fig. 16**. In the case of foundations with W/C of 50% or higher, sludge ejection was observed along with lifting of the tower, but these phenomena did not occur for the majority of foundations with W/C under 50%, paralleling the findings obtained from the present study. Further, the foundations where damage occurred were in snowfall areas, and foundations located in areas of rainfall only did not exhibit damage. Since the damage locations were all situated in snowfall areas, freeze-thaw action may have been a factor, but the facts that damage became evident in an extremely short time period of just a few months from entry into service, and that inspection reports make no mention of freeze-thaw issues, suggest that this is unlikely. In the case of rainfall, if there is no water accumulation, the rainwater dissipates a few hours after the weather dries up, but in the case of snowfall, the snow remains for several days even after the weather recovers, and liquid water is continuously supplied as snowmelt, a difference in water supply that is considered to account for this difference between rainfall and snowfall areas (Kunieda *et al.* 2012). It should be noted that even in the case of rainfall, prolonged water accumulation may occur if drainage is poor, giving rise to the same problem as with snowfall.

(2) Design and construction measures for the future
In light of the damage development mechanism revealed in this study, at sites where there is the possibility that liquid water will come in contact with the steel-concrete interface, it is advisable to suppress long-term pooling of liquid water at the interface, and further, to select materials and a structure that are less susceptible to the effects of liquid water. Specifically, the following measures may be considered.

a) Installation of drainage system
Given that the influence of liquid water is significant reduced if it does not remain at the interface between the steel and concrete or in cracks, providing drainage channels or an appropriate drainage gradient ensuring reliable drainage, or some other system to prevent ingress of liquid water, is effective. In the sense of reducing as much as possible the effect of water, it is also effective to provide some kind of cover to prevent rain and snow exposure. However, owing to the effect of condensation, water may still accumulate inside the cover, so combination with some kind of drainage system should be considered. Waterproofing through the application of sealant also has a certain life-prolonging effect, but since the long-term performance of the sealant cannot be guaranteed, such measure necessitates periodic maintenance.

b) Use of low W/C concrete
For a denser pore structure and to suppress bleeding, the W/C should preferably be kept at a low level of 50% or lower. Further, to suppress the formation of voids be-

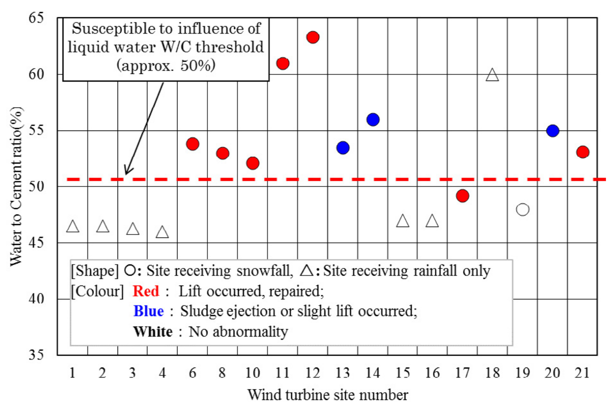


Fig. 16 Relationship between lifting of tower, W/C, and environmental conditions.

tween different materials caused by the shrinkage of concrete, use of low-shrinkage concrete is considered beneficial.

c) Change to a structure that inhibits the effect of water

The anchor-ring method examined in this study and the degraded bridge supports reported by Matsuda in 2013 are both designed to fix steel members to concrete by embedding them in concrete. In the case of the anchor-ring method, the ingress of water from the interface causes the degradation of concrete in internal closed spaces, leading to rapid deterioration of anchorage performance.

However, until now there have been no reports of abnormalities in wind turbine foundations anchored with the anchor-bolt method, and thus this method may be said to be less susceptible to the action of liquid water. This is thought to be due to the fact that in the case of the anchor-bolt method, the load transfer mechanism from the wind turbine tower differs from that of the anchor-ring method. In case of anchor-bolt method, the tower is fixed by prestressing force through bolt tightening. In this case, the foundation is kept under compression state, and drawing in of water is hard to occur. As a result, the anchorage performance of the anchor-bolt method is not much influenced by liquid water. If it is allowed to select or change the anchoring method, it is preferable to use anchor-bolt method to inhibit the influence of liquid water. For the existing structures which are difficult to change the structural system, installation of drainage system and putting cover seems to be the most practical and effective countermeasures.

6. 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 deteriorated sharply.

(2) Even when the steel-concrete bond is sound, subjection to repeated action makes liquid water ingress from the interface possible.

(3) In the presence of liquid water, the anchorage performance of concrete is significantly decreased owing to promotion of breakdown by the wedge effect caused by the viscous behavior of liquid water, promotion of breakdown by continuous exposure of intact surfaces to fragments transported in water, and promotion of breakdown by grinding of inner concrete surface by sludge particles and cavitation erosion.

(4) When water is present under the action of cyclic loading, the wedge effect occurs in fine cracks and in pore voids. The promotion of breakdown by liquid water can be mitigated by lowering the W/C of concrete for the denser structure and enhanced impermeability, and lowering the loading rate to prevent the wedge effect.

(5) When liquid water is present under the action of cyclic loading, the fragments generated from the breakdown of concrete are transported as sludge, continuously exposing intact surfaces to external forces and accelerating damage development.

(6) Breakdown may be promoted by actions such as grinding by sludge particles and cavitation erosion caused by advection of liquid water containing sludge through voids. Quantitative analysis of such breakdown promoting action by liquid water needs to be done in the future.

(7) As liquid water supply through snowfall spans long periods, liquid water ingress from the steel-concrete interface is facilitated and degradation of anchorage performance by liquid water results. Even in the case of rainfall, if prolonged pooling of liquid water is possible due to poor drainage, the same problem as with snowfall may occur.

(8) To reduce the effect of liquid water on a structure, the provision of a drainage system or structure and also a system or acccesaries to prevent water ingress is effective. Additionally, the use of low W/C concrete or a structure type that reduces the effect of water would also allow more effective mitigation of the effect of liquid water.

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References

Gebreyouhannes, E., Kishi, T. and Maekawa, K., (2008). "Shear fatigue response of cracked concrete interface." *Journal of Advanced Concrete Technology*, 6(2), 365-376.

Gilkey, H. J., (1926). "The effect of varied curing conditions upon the compressive strength of mortar and concrete." *Proceedings of ACI*, 22, 395-436.

Graham, J. R., Hamilton, W. S., Hendrickson, J. G., Kaden, R. A., McDonald, J. E., Noble, G. E. and Schrader, E. K., (1987). "Erosion of concrete in hydraulic structures." *ACI Materials Journal*, 136-157.

Ishibashi, T., Sakata, K., Kojima, T., Matsushita, H., Kishitani, K. and Nishizawa, N., (1987). "*Durability of the concrete structures -Fatigue-*". Giho-do shuppan, Tokyo. (in Japanese)

Kunieda, M., Chijiwa, N., Ohara, K. and Maekawa, K., (2012). "Feasibility study of autonomous deformation control of PC viaducts, From Materials to Structures - Advancement through Innovation -." In: Samali, Attard & Song (Eds.), Taylor & Francis Group, London, 313-318.

Maekawa, K. and Fujiyama, C., (2013). "Ratedependent model of structural concrete incorporating kinematics of ambient water subjected to high-cycle loads." *Engineering Computations*, 30(6), 825-841.

Matsuda, Y., (2013). "Control of water for the durability of the concrete structure (1) Influence of the water on the deterioration and damage of the concrete structures." *Concrete Journal*, 51(10), 814-818. (in Japanese).

Matsui, S., (1987). "Fatigue strength of RC-slabs highway bridge by wheel running machine and influence of water on fatigue." *Proceedings of JCI*, 9(2), 627-632. (in Japanese)

Matsushita, H., (1984). "Compressive strength of concrete under submerged condition." *Journal of JSCE*, 296, 87-95. (in Japanese)

Matsushita, H. and Onoue, K., (2006). "Influence of surface energy on compressive strength of concrete under static and dynamic loading." *Journal of Advanced Concrete Technology*, 4(3), 409-421.

Momber, A. W., (2000). "Short-time cavitation erosion of concrete." *Wear*, 241(1), 47-52.

Slowik, V. and Saouma, V., (2000), "Water pressure in propagating concrete cracks." *Journal of Structural Engineering*, 126(2), 235-242.