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ENVIRONMENTAL IMPACT DUE TO SALT WATER DISPERSED FROM UPPER POND OF SEAWATER PUMPED STORAGE POWER PLANT

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GENERAL

Pumped storage power plants (hereinafter referred to as PSPPs) bring both quantitative and qualitative improvements to the electricity generation system. PSPPs occupy approximately 10% of Japan's total power plant capacity. Therefore, it is anticipated that there will be a growing demand for the development of PSPPs in parallel with an increase in electricity consumption.

In this context, a seawater PSPP (hereinafter referred to as a SWPP) located on the coast and which uses seawater for operation of the power plant, has been studied over the past 15 years. Dispersion of seawater from an upper pond of SWPP is a concern as well as corrosion of power plant materials concerning the effects on the environment due to the utilization of seawater. Several countermeasures designed to resolve these issues have been verified in the demonstration SWPP (maximum capacity of 30 MW) shown in Fig. 1 which is located in the southern part of Japan in Okinawa. The specifications of the demonstration power plant are shown in Fig. 1 (METI and J-POWER, 2004).

Items		Unit	Specified
Power generation plan	Effective head	m	136
	Maximum power discharge	m^3/sec	26
	Output	MW	30
Upper pond	High water level	m	EL+152
	Low water level	m	EL+132
	Water surface area	km^2	0.05
	Effective storage capacity	m^3	$0.56x10^6$
	Type of dam	-	Fill dam
	Height	m	25
	Crest length	m	848
	Embankment volume	m^3	$420x10^3$

Fig. 1 Features of SWPP in Okinawa

The issue of the dispersion of saltwater, which has potential harmful effects on the surrounding area, is discussed in this paper. The dispersion of saltwater from the sea and the upper pond could cause salt damage to plants and vegetation around the power plant. The monitoring of salt dispersion was conducted to clarify these effects. In addition, a simulation using a salt dispersion model has also been studied for a future commercial SWPP project based on the monitoring data obtained from the demonstration SWPP.

FEATURES OF UPPER POND OF THE DEMONSTRATION SWPP

The upper pond has an octagonal shape, is 252 m wide and has a storage volume of 560000 m^3 between the high water level of EL 152 m and the low water level of EL 132 m. The area of the upper pond is 0.05 km^2 at the high water level. It is located 550 m inland from the sea and is surrounded by a dense oak forest that is typical of this area as shown in Fig. 1. It is faced entirely with EPDM rubber sheeting to prevent seawater from infiltrating the foundations.

The upper pond of the demonstration SWPP was impounded firstly in 1998. It is operated daily between the high and the low water levels when wind conditions are normal. However, during severe wind conditions, such as those that occur during typhoons, operation is suspended to prevent damage to the rubber sheet facing due to its swelling (Kashiwayanagi, et al., 2006).

MONITORING ON DISPERSION OF SALT WATER

Monitoring method

To assess the influence of the dispersion of salt water from the upper pond, monitoring is carried out. The salt particles around the upper pond come not only from the upper pond itself but also from the sea. Therefore, the combined amounts of salt particles from both sources are monitored.

The salt content of the air (hereinafter referred to as atmospheric salt content), in the soil (hereinafter referred to as osmotic salt content of soil), and on the leaves of plants (hereinafter referred to as amount of salt deposited on leaves) are monitored. Among the above, atmospheric salt content is essential to evaluate the influence of the upper pond on the surrounding environment, since the osmotic salt content of soil and the amount of salt deposited on leaves are both derived from the salt particles in the air. The monitoring methods and the equipment utilized are summarized in Table 1 and shown in Fig. 2. The monitoring was carried out between 1997 and 2003. The locations of the monitoring sites are shown in Fig. 3.

Fig. 2 Equipments for monitoring of airborne salt content

Table 1 Monitoring of dispersion of the salt particles around the upper pond

Monitoring	Description
Atmospheric salt content	Salt contents of sucked air, Equipments for monitoring are shown in Fig. 2 as a example.
Osmotic salt content of soil	Salt content of the soil from the ground surface to 15 cm or 20cm deep
Amount of salt deposited on leaves	Measuring is made using dry leaves, picked at monitoring points
Particle size of dispersed salt	Farlow method

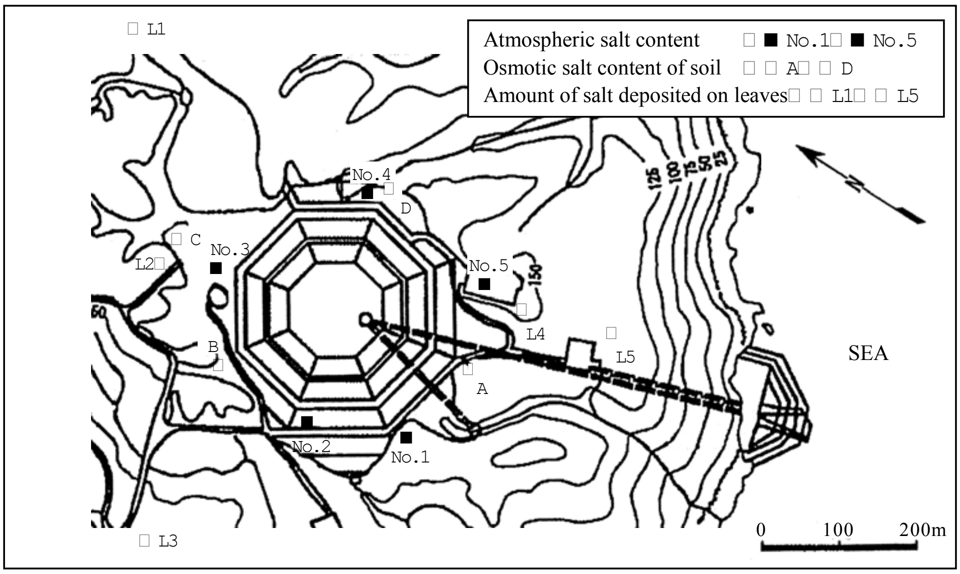

Fig. 3 Monitoring points of salt dispersion

Salt dispersion

<u>Atmospheric salt content</u>

The trend of monthly averages for atmospheric salt content, measured at the monitoring points No.1 to No.5 in Fig. 3, is shown in Fig. 4. The values, ranging from 1 to 10 μg/m^3, are those observed under normal wind conditions and show little change before and after the impoundment of the upper pond.

The atmospheric salt content under a strong wind condition is in the range of about 5 to 40 μg/m^3 during the years of 2001 to 2003, and is studied here to clarify the influence of the upper pond. The monitored data at the points of No.3 and No.5, which are located at the opposite side of the upper pond as shown in Fig. 3, are focused. Two major wind

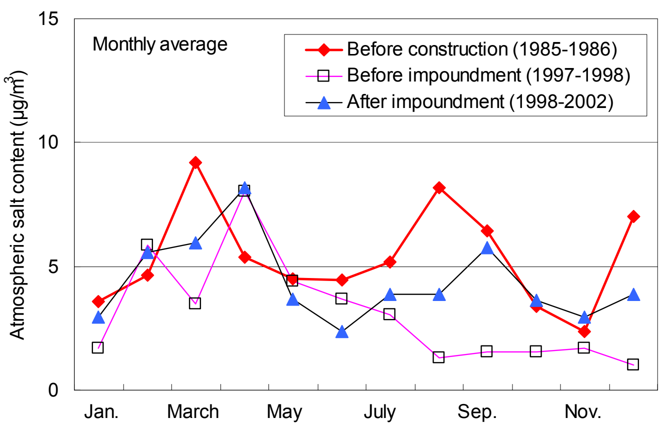

Fig. 4 Trend of atmospheric salt content (Normal wind condition)

directions through No.3 and No.5 points are selected, one from the sea side and another from the land side which is opposite side of the sea side. Case 1 in Fig. 5 shows the relation of the atmospheric salt contents between the aforesaid two points for the winds coming from the sea such as southeast, south and southwest directions.   In the same way, Case 2 shows the relation between the aforesaid two points for the winds coming from the land side, such as northwest, north and northeast. The most of data shown in Case 1 are in the area of No.3□No.5 for the winds coming from the sea, and the most of data shown in Case2 are in the area of No.3□No.5 for the wind coming from the land side. It can be said from these results that no significant influence is found in terms of the salt dispersion originated from the upper pond.

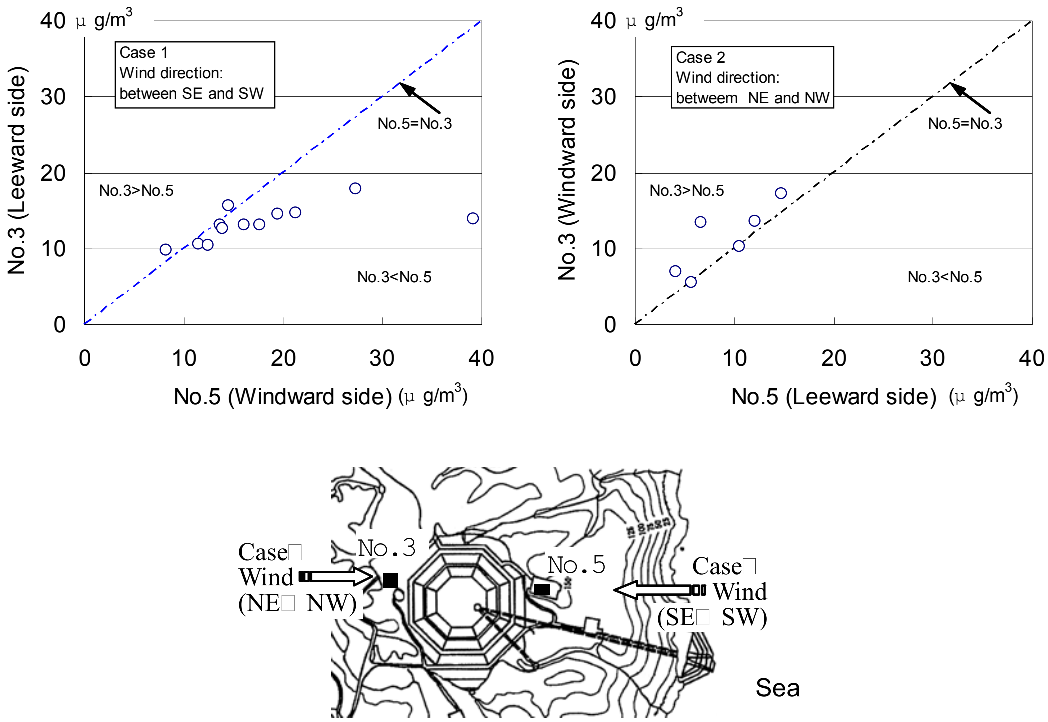

Fig. 5 Atmospheric salt content of No.3 point to No.5 point (strong wind condition)

<u>Osmotic salt content of soil</u>

The influence of the upper pond was studied by analyzing the data on the osmotic salt content of soil around the upper pond. Fig. 6 shows the osmotic salt content measured at the monitoring points A to D in Fig. 3, during strong winds such as typhoons. The measurement period of 1997 to 2003 includes August 1998 when the upper pond was impounded. The osmotic salt contents of soil for all measurement points tend to increase, and shows a very high values from 100 to 340 mg/kg regardless of the impoundment of upper pond, after the occurrence of strong winds. These values gradually decrease in a certain months to 17.4 mg/kg (dotted line) under normal wind conditions. There are monitoring points where very high osmotic salt content of soil persists for several months after strong winds. It is considered that these data of osmotic salt content of soil are affected predominantly by the topographical condition surrounding the monitoring points.

<u>Amount of salt deposited on leaves</u>

The amount of salt deposited on leaves was monitored around the upper pond after the impoundment and the results are shown in Fig. 7. These results include data collected during typhoons. The data under normal wind conditions range from 0.1 to 0.87 mg/kg. These values increase to 0.5 to 2.0 g/kg following typhoons, which is a significant increase. However, data collected at the points of L1 and L3 which are located at 400 m and 800 m from the upper pond and the sea respectively, show at most 0.5 g/kg.

Significant result indicating the influence due to salt dispersion of upper-pond-origin could not be identified.

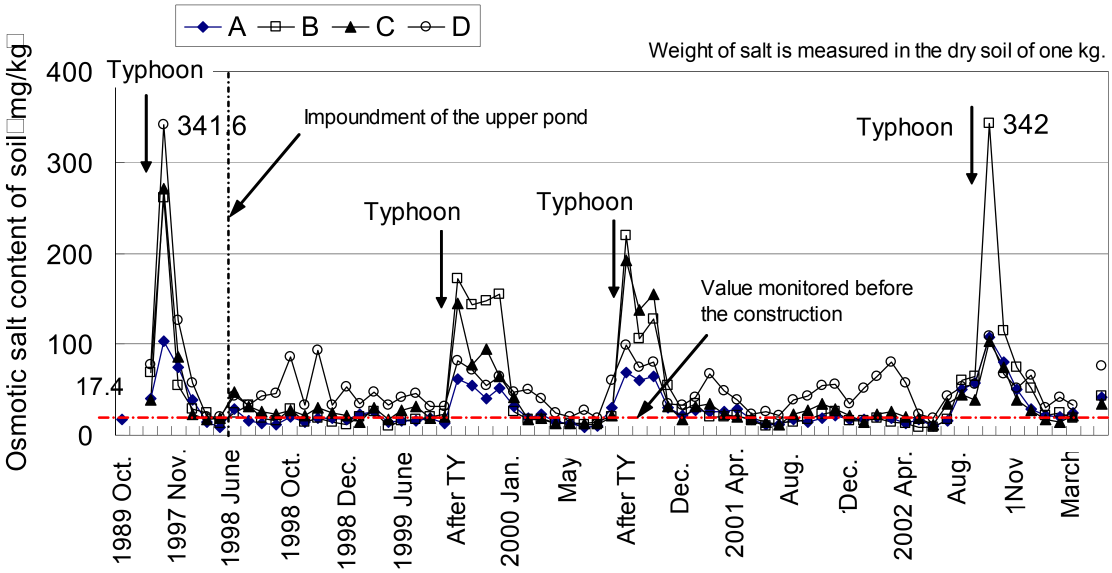

Fig. 6 Trend of osmotic salt for soil

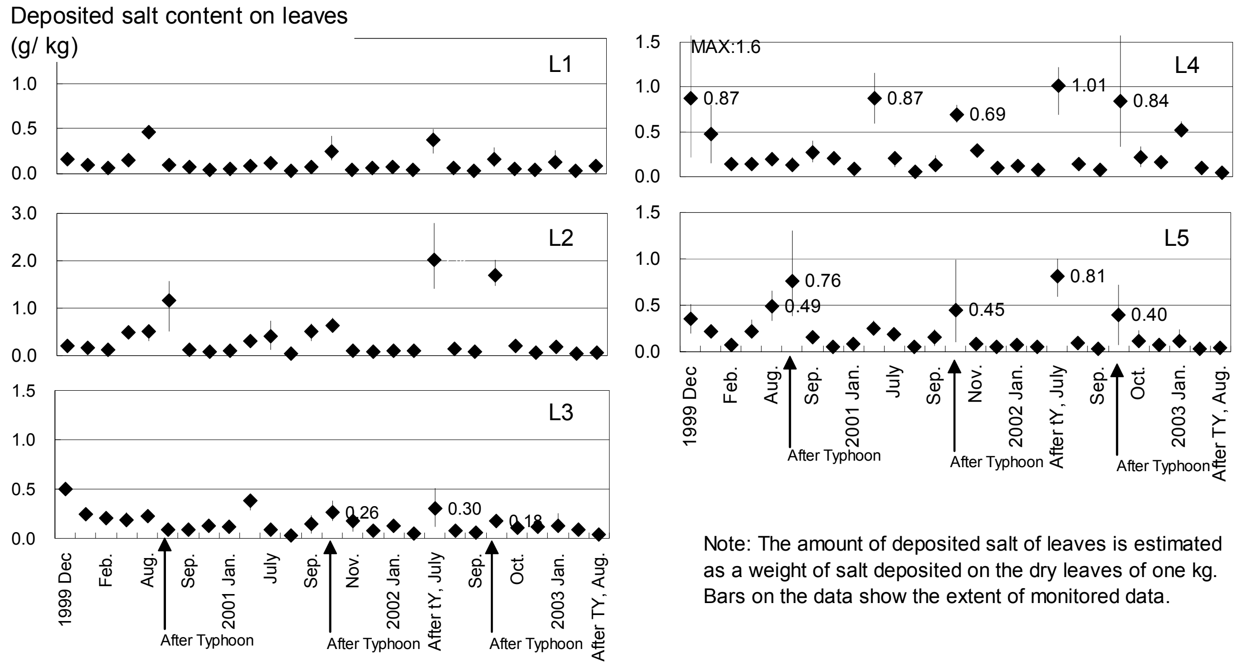

Fig. 7 Trend of salt deposited on Leaves

Evaluation on monitoring of salt dispersion from the upper pond

The following conclusions were derived from the monitored data.

(1) Very high values were occasionally found for the osmotic salt content of soil, with these values tending to be affected by the local terrain. In addition, the amount of salt deposited on leaves is affected by local vegetal conditions, such as height, adjacent planting conditions and density of leaves etc. Therefore, the environmental impact of salt dispersion from the upper pond could not be evaluated by examining the osmotic salt content of soil or the amount of salt deposited on leaves. However, atmospheric salt content shows predictable changes corresponding to the prevailing wind characteristics. The atmospheric salt content is an appropriate index for evaluating the environmental impact due to salt dispersion originating from the upper pond.

(2) Little influence is found on the surrounding environment due to the dispersion of salt particles from the upper pond under normal wind conditions.

(3) The atmospheric salt content increase temporarily during strong winds. The results obtained from the monitoring points do not show clearly the influence of salt dispersed from the upper pond, regardless of the wind direction. It is considered that the salt particles around the upper pond predominantly come from the sea even under strong wind conditions.

(4) An analysis of the above-mentioned monitored data on salt dispersion for the demonstration SWPP revealed that salt particles from the upper pond have less impact on the surrounding area than particles from the sea, even under strong wind conditions.

SALT DISPERSION SIMULATION

Outline of the method

The impact on the environment due to salt dispersion originating from the upper pond (hereinafter upper-pond-origin) during strong winds could not be clearly ascertained from monitoring results obtained for the demonstration SWPP as described above. Since the upper pond of a commercial power plant is much larger in scale than that of the demonstration SWPP, there might be concerns about the environmental impact due to salt dispersion of upper-pond-origin. Thus, it is necessary to evaluate the impact of such a plant before its construction by conducting a numerical analysis to address these concerns. To perform such evaluation, the following method (CRIEPI, 2004) was developed. As shown in Fig. 8, amounts of salt dispersion originating from the sea (hereinafter “sea-origin”) and upper-pond-origin are calculated based on input data for topographical and weather conditions. Then, atmospheric salt content for arbitrary points are calculated, taking into account diffusion and settling. Since salt dispersion of sea-origin and upper-pond-origin are calculated separately, both values should be added together to estimate the impacts due to possible dispersion of stored seawater in the upper pond. In this section, only atmospheric salt content is focused on, as this is the most important factor.

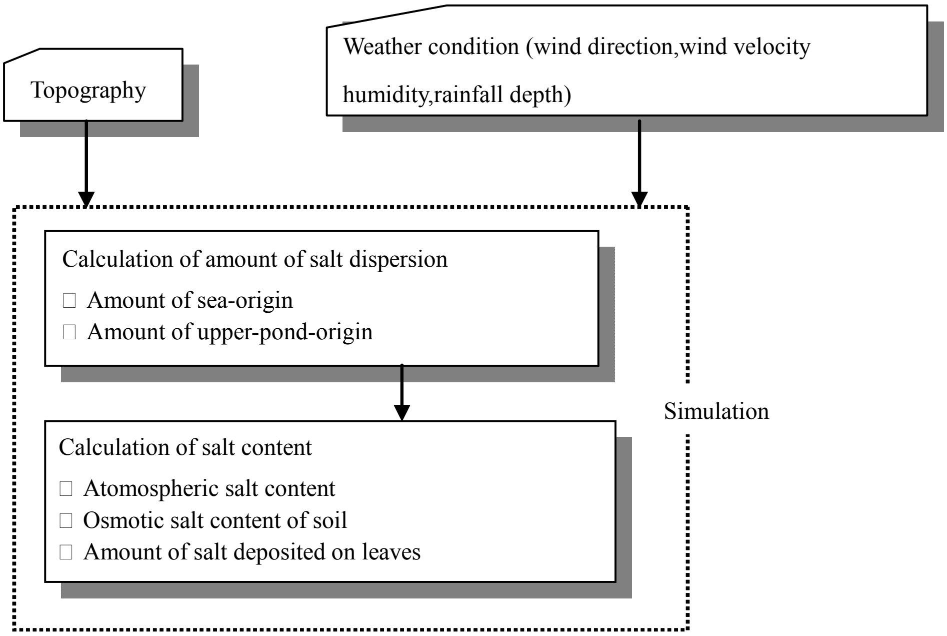

Fig. 8 Calculation procedure

Estimation of atmospheric salt content of sea-origin

The "Slated fume-centered total settling model" is applied taking gravitational settling speed into account. As shown in Fig. 9, it is assumed that sea-salt particles pass from windward to leeward through an infinitesimal area of ΔH×ΔS at the centering point P(0,s,H) which is a part of a vertical plane along the coastline(X=0□. Then, considering the diffusion of salt particles, contribution to a point of A(X, Y, Z) located on the leeward side is estimated. Assuming the whole vertical plane along the coastline supplies sea salt particles, the amount contributed from all the points of the plane are summed for each particle size. Thus, atmospheric salt content is calculated for the points.

To make this easy to understand, the following explanation is made for a specific salt particle size. Assuming that the sea-salt particles come from point P(0,s,H), and the content of sea salt particles is a function only related to height, the content C(x, y, z) of an arbitrary point A(x, y, z) is expressed by the formula (1). Since the sea-salt particles are in a mist state, it is assumed that all particles settle on the ground surface, thus, formula (1) excludes the reflection term.

The other factors such as shield effect due to topography, effect of precipitation affecting the state of the sea salt particles, etc. can be estimated, by introducing the appropriate parameters.

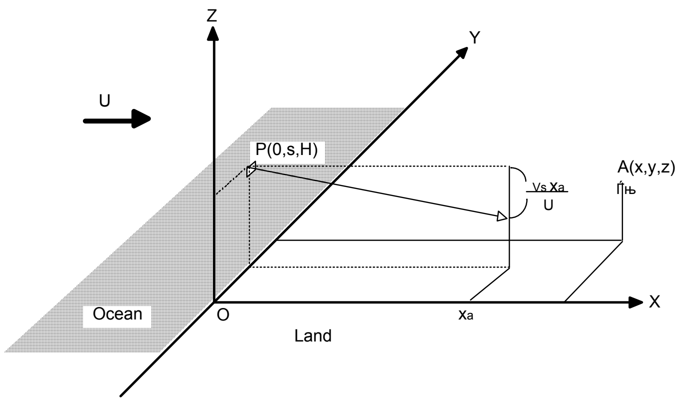

Fig. 9 Model on Prediction of salt Dispersion

$$C(x,z)=\int_0^{\infty}\frac{Q(H)}{\sqrt{2\pi}\,U\,\sigma_z}\exp\left\{-\frac{\left(H-z-V_s\dfrac{x}{U}\right)^2}{2\sigma_z{}^2}\right\}dH \tag{1}$$

Where, $Q(H)$□amount of diffusing material□1/s□, U□wind velocity at representative height□m/s□, $\sigma_z(x)$□diffusing width in z-direction□m□, V_s□gravitational settling rate of salt particle□m/s□

Estimation of atmospheric salt content of upper-pond-origin

The method used to estimate atmospheric salt content of upper-pond-origin is basically same as that used for sea-origin as described above. However, assuming that the source of sea-salt particles exists in the vertical plane of the leeward edge(x=0) of the upper pond and the width of the upper pond is finite, formula (2) is applied instead of formula (1).

$$C(x,y,z)=\int_{-L/2}^{L/2}\int_0^{\infty}C'(x,y,z)\,dH\,ds \tag{2}$$

Verification of the Method

As a verification of the proposed method, a comparison between observed values of atmospheric salt content and estimated values during strong winds, mainly typhoons, was made. Input data of wind velocity and wind direction, and a comparison of observed and estimated values for atmospheric salt content are shown in Fig. 10.

The estimated values for No.3 and No.5 sites, as shown in Fig. 10, are generally higher than or close to the observed ones, although the simulation model places on the safety side's estimate for commercial SWPPs. It can be said that this simulation model can reliably estimate the environmental impact due to dispersion of salt particles at the commercial SWPPs. A simulation of the impact of salt dispersion originating from the upper pond for commercial power plants is described in the next section.

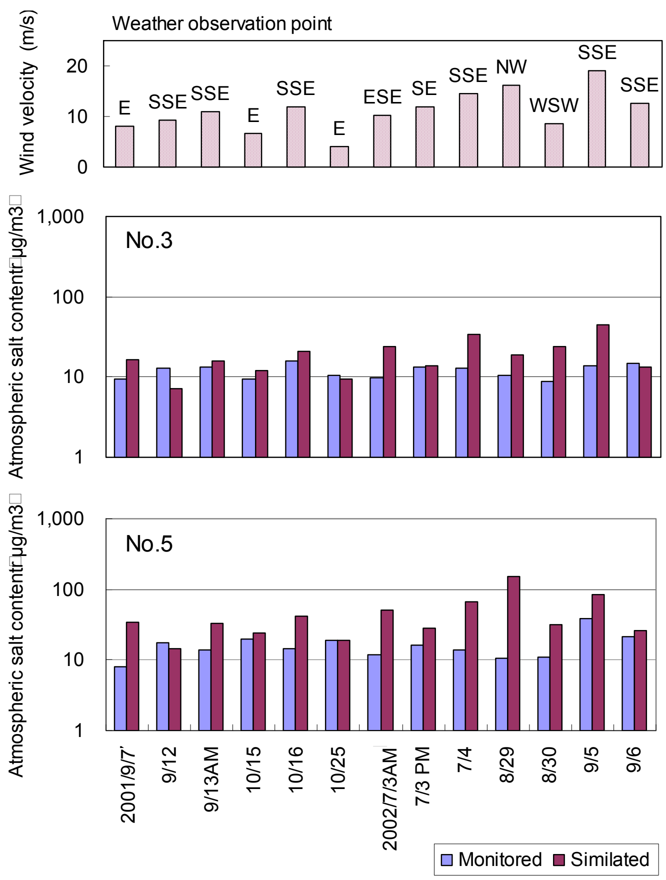

Fig. 10 Comparison between observed and estimated values

APPLICATION OF SIMULATION MODEL TO COMMERCIAL POWER PLANTS

Conditions

Since the installed capacity of commercial SWPP is in the 1000 MW class, the storage capacity of the upper pond needs to be much larger than that of the demonstration SWPP (30 MW). Upper ponds for power plants are placed at an elevation of 300 m to 400 m above sea level for economic reasons. Factors affecting atmospheric salt content are wind velocity, scale and elevation of upper ponds, arrangement of tide-water control forest, etc. By using these parameters, atmospheric salt content of 1 m above the land surface is analyzed for commercial SWPPs.

Condition for the analysis and a conceptual image are shown in Table 2 and Fig. 11 respectively.

Table 2 Condition of Analysis

Parameter	Condition
Wind Velocity	20m/s, 25m/s
Elevation of Upper Pond	H: 140m (Demonstration SWPP), 300m, 400m
Distance from sea of the upper pond	L: 500m Distance of 0m is assumed from sea to cliff
Scale of Upper Pond	Width 500m, Length B: 1000m
Tide-water control Forest	High of forest: h 5m,10m Distance from Leeward edge of Upper Pond, L': 10m

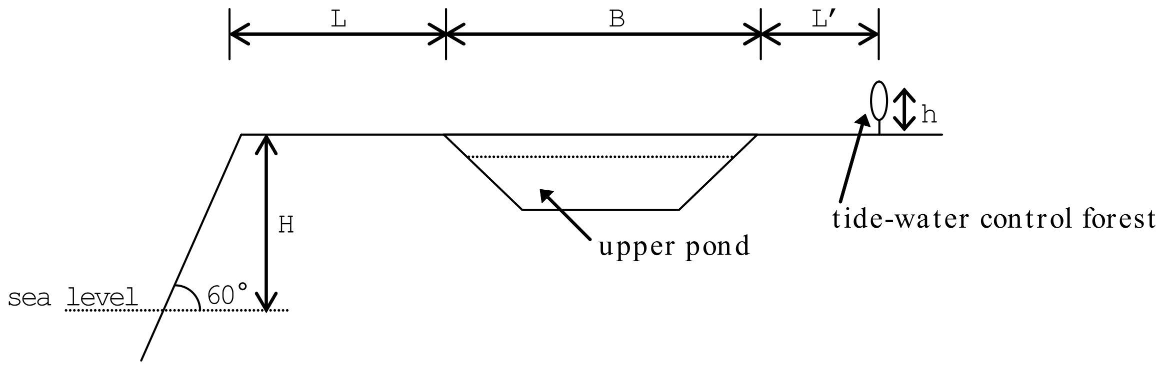

Fig. 11 Relation between Sea and Upper Pond

Results of the Analysis

Atmospheric salt content of sea-origin

In order to determine the background atmospheric salt content, which means that of sea-origin only, analysis excluding the upper pond is carried out. Calculation results are shown in Fig. 12(1).

The stronger the wind becomes, the more the atmospheric salt content increases. The atmospheric salt content for a wind velocity of 25 m/s is about double that for 20 m/s. The lower the elevation of the upper pond is, the more the atmospheric salt content increases. The atmospheric salt content (thin line) for the elevation of 300 m above sea level is about 1.5 times that (dotted line) for 400 m at the same wind velocity. The value (thick lines) of the elevation of 140 m shows for the demonstration SWPP. The atmospheric salt content is almost constant from the coastline to a point 1000 m inland; however, it decreases significantly for distances beyond 1000 m.

Atmospheric salt content of upper-pond-origin

In order to study the impact caused by an upper pond, the atmospheric salt content is analyzed under the condition that the source of salt particles is the upper pond only. The results are shown in Fig. 12 (2) which also includes the results for the atmospheric salt content of sea-origin. The characteristics are as follows.

Since the atmospheric salt content of wind velocity 25m/s is about 100 times of that of 20m/s, wind velocity is clearly the determining factor.

Atmospheric salt content of upper-pond-origin (thick line) is higher than that of sea-origin (thin line) for the distance of about 1000m where the wind velocity is 25 m/s; however, the atmospheric salt content of upper-pond-origin (thick line) is lower than that of sea-origin (thin line)where the wind velocity is 20 m/s. In the case where wind velocity is 25 m/s, the attenuation of the atmospheric salt content of upper-pond-origin (thick line) is more clearly observed than for that of sea-origin (thin line).

The effectiveness of a tide-water control forest (dotted line) to reduce the influence of airborne salt is significant in the vicinity of the forest, however it decreases as the distance from the forest increases. The effectiveness is limited to distances no greater than 1000 m beyond the limit of the forest and it depends on the height of the trees. In the case where wind velocity is 25 m/s, it is possible to reduce the influence of airborne salt of upper-pond -origin by planting a tide water control forest. And in order to prevent airborne salt from upper ponds, countermeasures such as planting tide water control forests at intervals of several hundred meters is useful.

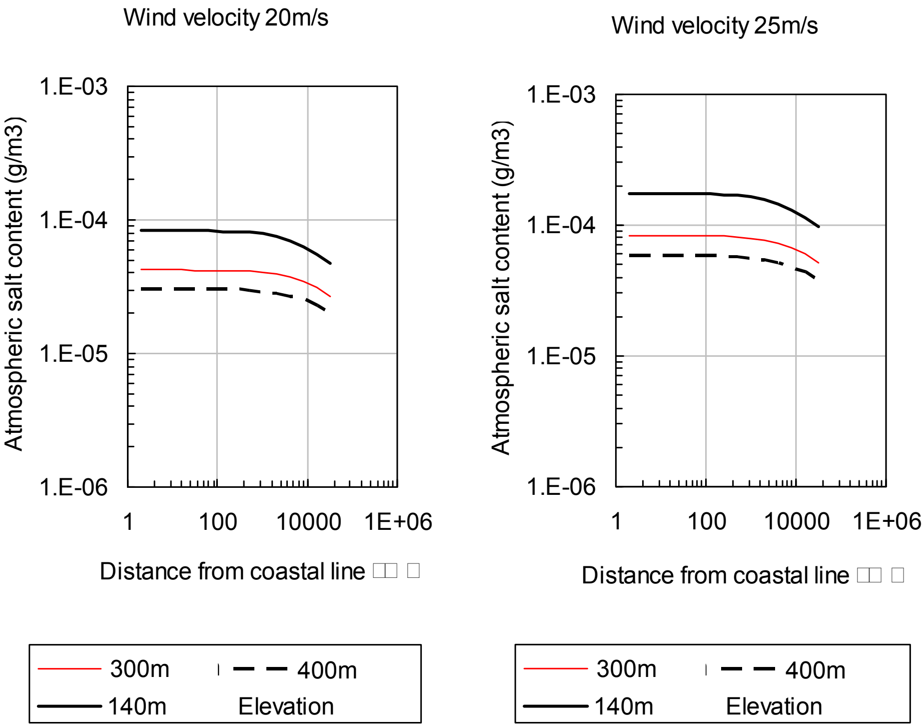

Fig. 12(1) Atmospheric salt content of Sea-origin

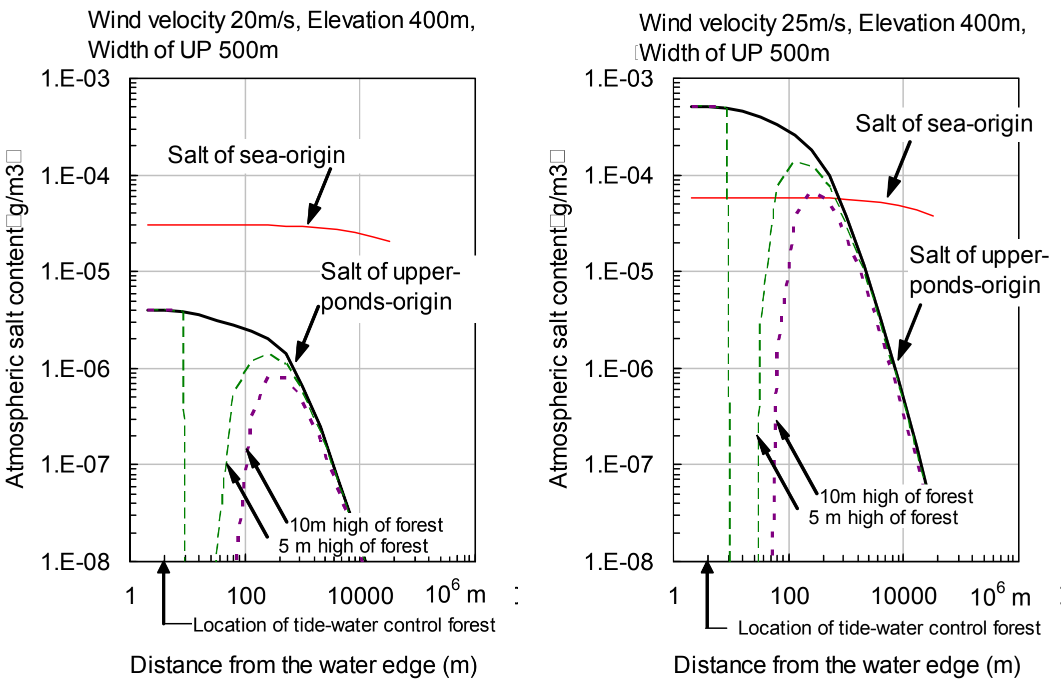

Fig. 12(2) Atmospheric salt content of upper-pond-origin

CONCLUSIONS

The following are the conclusions of this paper.

(1) As a result of monitoring the demonstration SWPP under strong wind conditions such as typhoons, salt dispersion, which was presumed to be of upper-pond-origin, could not be clearly confirmed. This result suggests that the salt dispersion of sea-origin is predominant and the environmental impact of dispersion of upper-pond-origin is relatively small.

(2) As a result of a simulation analysis, salt dispersion is affected significantly by wind velocity and the altitude of the upper pond. The atmospheric salt content of upper-pond-origin is shown to exceed that of sea-origin for a certain magnitude of wind velocity. With the attenuation of atmospheric salt content correlated to distance, the simulation showed that the rate of attenuation of airborne salt content of upper-pond-origin is larger than that of sea-origin. This means that the impact of salt dispersion of upper-pond-origin is insignificant compared to that of sea-origin. A tide water control forest which is planted at the leeward of the upper pond is expected to have a significant effect.

(3) Since the results of the estimation using the model agree with the monitored results in the demonstration SWPP reasonably well, the proposed simulation method is applicable to the design of upper ponds for commercial SWPP and contributes to mitigate the environmental impact caused by salt dispersion from upper ponds.

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