Risk analysis of airplane accidents due to bird strikes using Monte Carlo simulations

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Abstract

Airplane accidents are generally more serious than accidents involving other methods of transportation. One cause of airplane accidents is a collision with a bird, which is called a bird strike. Particularly, if the bird is ingested by the jet engine, the airplane may lose power and crash. Therefore, it is useful to understand the bird strike risk before opening a new airport.

In this paper, the bird strike situation at existing airports in Japan is investigated, and the frequency and factors of bird strikes are presented (including geographic information, the number of takeoffs and landings, land use around the airport, and so on). Also, the relationships between these various factors and bird strike occurrence are analyzed. Furthermore, risk analysis is performed using Monte Carlo simulations of Haneda Airport as an example (which is the biggest airport in Japan), and bird strike countermeasures are suggested.
Keywords: bird strike, airport, airplane, risk analysis, Monte Carlo simulation.

1 Introduction

Upon takeoff or landing, an airplane can potentially collide with a bird, which is known as a bird strike. If a large bird were to be ingested by a jet engine, a serious accident may occur. According to a report by the Federal Aviation Administration (FAA), about 108,000 bird strikes occurred in the USA from 1990-2009 [1].

Based on bird strike data in Japan, the number of bird strikes that have occurred varies by region. If bird strike precautions are considered during the construction of a new airport, the risk can be significantly reduced.

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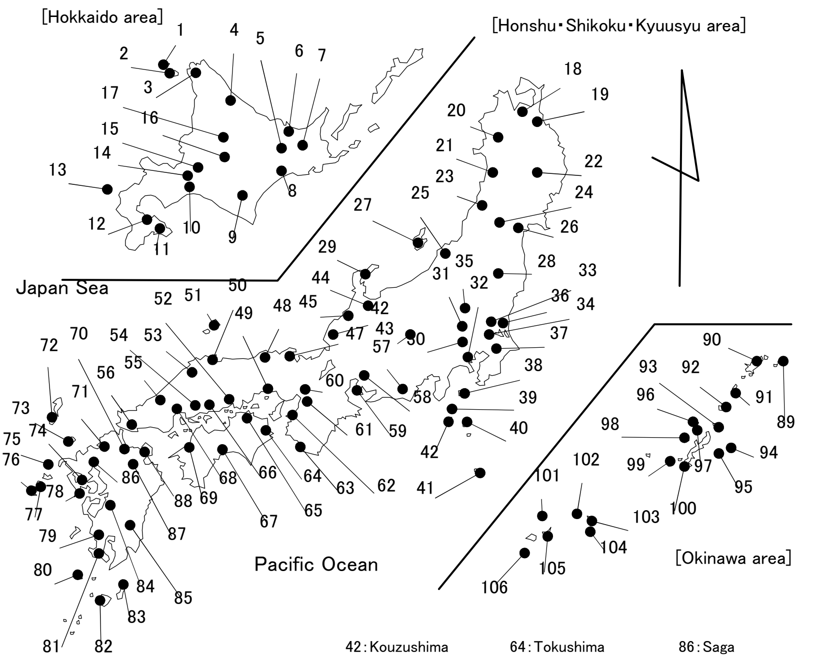
For this study, a questionnaire was distributed to airport officials regarding bird strike events at their respective airports. Also, all airports in Japan were investigated in terms of location and usage (such as the number of takeoffs and landings). Based on the results of the investigations, bird strike factors were analyzed and precautions were proposed for the development of new airports. Furthermore, as an example, the bird strike risk at Tokyo’s Haneda Airport was analyzed using Monte Carlo simulation and bird strike countermeasures were suggested.



1 : Rebun
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4 : Mobstsu
5 : Deshikutu
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11 : Hakodate
12 : Shikabe
13 : Okushiri
14 : Chitose
15 : Okadama
16 : Asahikawa
17 : Aibetsu
18 : Aomori
19 : Misawa
20 : Oodate-Noshiro
21 : Akita
22 : Hanamaki
23 : Shounai
24 : Yamagata
25 : Niigata
26 : Sendai
27 : Sado
28 : Fukushima
29 : Noto
30 : Choufu
31 : Honda Airport
32 : Haneda
33 : Ami
34 : Ryuugasaki
35 : Ootone
36 : Ibaragi
37 : Narita
38 : Ooshima
39 : Niijima
40 : Miyakejima
41 : Hachijyoujima
42 : Kouzushima
43 : Matsumoto
44 : Toyama
45 : Komatsu
46 : Fukui
47 : Tajima
48 : Tottori
49 : Kobe
50 : Yonago
51 : Oki
52 : Okayama
53 : Izumo
54 : Hiroshima
55 : Iwami
56 : Yamaguchi-Ube
57 : Shizuoka
58 : Nagoya
59 : Chubu
60 : Itami
61 : Yao
62 : Kansai
63 : Nanki-Shirahama
64 : Tokushima
65 : Takamatsu
66 : Okanan
67 : Kouchi
68 : Hiroshima-Nishi
69 : Matsuyama
70 : Kitakyuusyuu
71 : Fukuoka
72 : Tsushima
73 : Iki
74 : Nagasaki
75 : Konega
76 : Fukue
77 : Kamigotou
78 : Amakusa
79 : Kagoshima
80 : Satsuma-Ioutou
81 : Makurasaki
82 : Yakushima
83 : Shin-Tanegashima
84 : Kumamoto
85 : Miyazaki
86 : Saga
87 : Ooita-Kenou
88 : Ooita
89 : Kikai
90 : Amami
91 : Tokunoshima
92 : Okinoerabujima
93 : Yoron
94 : Kita-Daitoujima
95 : Minami-Daitoujima
96 : Awakuni
97 : Iejima
98 : Kumejima
99 : Kerama
100 : Naha
101 : Yonaguni
102 : Tarama
103 : Shimochijima
104 : Miyako
105 : Ishigaki
106 : Hateruma

Figure 1: Locations of airports (in 2009).

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2 Current bird strike situation

International Birdstrike Committee (IBC) recommended the standards for Airdrome Bird/Wildlife Control in 2006 [2]. However, in present day, multiple bird strike incidents have occurred each day throughout the USA. In some cases, these bird strikes caused serious accidents. In 1960, an airplane took off at Boston Airport and each of the four engines ingested starlings [1]; as a result, the airplane crashed and 62 lives were lost. Recently, in 2009, an airplane made a forced landing on the Hudson River in New York due to a bird strike [3].

As of 2009, there were 106 airports in Japan, as shown in Figure 1; without exception, bird strikes have occurred at every airport. In Japan, despite efforts by the airports, an average of about 1,200 bird strikes have occurred annually from 2004-2008 [4]. Fortunately, in Japan, although serious accidents due to bird strike have not occurred, delays and suspensions of service have often occurred due to fuselage or engine damage from bird strikes.

3 Investigation summary

3.1 Questionnaire

A bird strike questionnaire was distributed to the officials of 70 airports at which there has been regular flight service. The content of the questionnaire is shown in Table 1. Also, the environmental conditions (precipitation; surrounding areas, e.g., residential areas, farmland, forests, seas, lakes, and cultivated fields; and the distance between the airport the nearest body of water) were determined, and the relationships between these factors and bird strike occurrence were analyzed. For the surrounding areas, a 3 km radius from the center of the airport was used, as shown in Figure 2. Also, regarding the distance between the airport and bodies of water, the shortest distance from airport to the coastline was measured, as shown in Figure 2.

Table 1: Questionnaire for airport officials.

Do you give us information of your airport on BS as below:
Q1. The number of cases of BS.
Q2. The number of times on the takeoff and landing for the last five years.
Q3. The number of users a year.
Q4-1. Measures against BS at the time of planning for the construction of airport.
Q4-2. Measures against BS in present day.
Q5.The time that BS occurs most frequently.
Q6. The quantity of annual precipitation around the airport.
Q7. The weather when BS occurs.(temperature, hourly precipitation, wind)
Q8. The actual damage due to BS in your airport.
Q9. Problems to manage the airport.

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3.2 Risk analysis

Tokyo’s Haneda Airport was used as an example to analyze bird strike risk. 10% of the bird strikes in Japan have occurred at Haneda Airport [4]. Also, Haneda Airport recently opened a new runway, called “D runway”, as shown in Figure 3. The bird strike risk is estimated to be high in the future, because the number of runways increases from three to four.

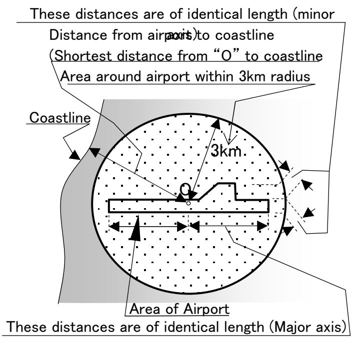

Figure 2: Measurement methods for bird strike factors.

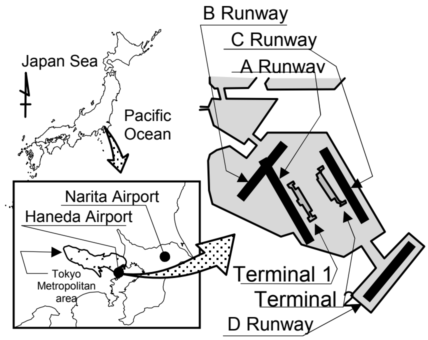

Figure 3: Plane view of Haneda airport.

A bird strike risk simulation for Haneda Airport was performed in Crystal Ball (Standard Pack, Oracle corporation) using a Monte Carlo simulation. To determine the parameters of the risk simulation, an inspection of Haneda Airport was performed, and videos were taken of airplane takeoffs and landings. Also, experts from Tokyo Port Wild Bird Park near Haneda Airport were consulted to gain an understanding of bird behavior.

4 Investigation results

4.1 Consideration of bird strike factors

Forty responses from airport officials were obtained; 33 airports were selected for the analysis of bird strike factors. The remaining seven airports have gotten rid of birds, and very few bird strikes have been reported.

Tables 2 and 3 show the questionnaire responses and the relationships between some relevant factors (the number of takeoffs and landings, the times when bird strikes occurred, precipitation and temperature, and land use around the airport) and bird strike occurrence. These relationships are explained below:

4.1.1 The number of bird strikes (Q1)

As shown in Table 2, bird strikes have occurred throughout Japan. The airport with the highest bird strike incident rate is Kobe Airport at 52 per year, or about

Table 2: Analysis of bird strike factors.

No.	Name	Annual averaged number of bird strike between 2004 and 2009	Averaged number of takeoff and landing between 2004 and 2009	Number of passenger in 2009	Averaged Amount of rainfall between 2004 and 2009	Temperature in 2009	Distance from sea or lake to airport
4	Monbetsu	2.2	1028	47,977	442	6.8	0.86
6	Memanbetsu	1.6	5699	893,618	477	6.4	4.26
7	Nakashibetsu	2.2	3304	176,240	1005	6.0	17.0
9	Obihiro	3.4	4719	609,938	779	7.2	31.2
18	Aomori	9.0	9151	1,140,383	1372	8.0	10.8
20	Oodate-Noshiro	4.7	2081	125,160	1547	10.0	28.8
21	Akita	27.8	7892	1,184,195	1579	12.0	13.4
22	Hanamaki	3.8	4251	361,185	2066	10.9	61.6
23	Shounai	12.7	3778	392,995	1681	12.9	1.44
24	Yamagata	2.6	5110	191,450	1192	12.1	55.2
28	Fukushima	5.4	7484	426,869	1264	13.5	52.2
29	Noto	2.8	2014	171,422	1962	13.3	6.21
43	Matsumoto	4.0	4137	63,484	1028	12.2	80.8
44	Toyama	23.6	5538	1,121,623	2107	14.6	12.1
48	Tottori	21.2	5228	306,516	1576	15.0	0.33
49	Kobe	52.0	9869	2,579,674	964	17.1	0.34
51	Oki	3.2	1836	31,926	1487	14.5	1.19
52	Okayama	23.6	6220	1,422,347	1038	16.6	20.1
53	Izumo	24.4	10696	755,656	1639	14.9	1.00
55	Iwami	10.0	1874	69,472	1536	15.9	1.00
56	Yamaguchi-Ube	14.8	3662	857,788	1470	16.1	0.32
64	Tokushima	13.0	4260	145,545	1014	16.9	0.98
76	Fukue	2.0	5017	147,689	2084	17.2	2.26
79	Kagoshima	34.8	33,084	5,426,911	2475	19.0	7.22
86	Saga	42.4	4603	297,832	1549	16.9	0.60
89	Kikai	4.75	3603	72,561	1797	21.9	0.30
90	Amami	20.4	7160	555,008	2766	21.8	0.26
91	Tokunoshima	6.5	1893	145,545	1788	21.9	0.10
92	Okinoerabujima	4.0	6110	85,983	1708	22.6	1.98
93	Yoron	6.25	1692	67,464	1758	22.9	0.99
103	Shimochijima	16.8	14063	0	1817	23.9	0.63
104	Miyako	24.6	7602	1,077,571	1957	10.8	3.12
105	Ishigaki	22.6	11925	1,845,317	2061	24.6	0.65
Correlation coefficient with number of BS			0.51	0.62	0.22	0.29	-0.32

one per week. However, the bird strike incident rate at Haneda Airport is higher than that of Kobe Airport [2].

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4.1.2 The number of takeoffs and landings and passengers (Q2 and Q3)

As shown in Table 2, the bird strike incident rate increases as the number of takeoffs and landings and passengers increases. The correlation coefficients for the numbers of takeoffs and landings and passengers based on bird strike frequency are 0.51 and 0.62, respectively; however, this is naturally to be expected.

4.1.3 The times that bird strikes typically occur (Q5)

Table 3 shows the time of day that bird strikes typically occurred for each airport. Note that half of the airports did not record the times at which bird strikes occurred. There is no apparent trend for the bird strike times among the various airports.

Table 3: Times of bird strike occurrences.

No.	Name	Times when BS is apt to occur	No.	Name	Times when BS is apt to occur
4	Monbetsu	Around noon	56	Yamaguchi-Ube	Between 17:00 and 20:00
7	Nakashibetsu	Between half past 12:00 and half past 13:00	76	Fukue	In the afternoon
21	Akita	Between 9:00 and 13:00	86	Saga	Around 14:00, around 18:00
22	Hanamaki	Around 10:00, around half past 14:30, and around 16:00	89	Kikai	Between 11:00 and 12:00
23	Shounai	Between 8:00 and 9:00	90	Amami	Between 7:00 and 10:00
44	Toyama	In the morning	91	Tokunoshima	Between 13:00 and 16:00
48	Tottori	After 16:00	103	Shimochijima	Between 11:00 and 12:00

4.1.4 Precipitation and temperature (Q6 and Q7)

As shown in Table 2, the bird strike frequency depends on the average precipitation and temperature. The precipitation in northeastern Japan is much less than in southwestern Japan, whereas the temperature in southeastern Japan is higher than in northeastern Japan. Therefore, bird strikes are more likely to occur at airports in southwestern Japan. In addition, regarding Q7, the answers from some respondents included the assessment that bird strikes were more likely to occur during rain events.

4.1.5 Bird strike mitigation efforts and problems due to bird strike (Q4, Q8, and Q9)

Some examples of actual bird strike issues from Q4, Q8, and Q9 are summarized as follows:

・Despite efforts to removal nesting places at the airport, nesting places appeared in other neighboring areas.

・The grass that is cut to inhibit nesting has been given to neighboring farmers who breed domestic animals. Therefore, the airport cannot use agricultural chemicals such as herbicides. As a result, the airport site has become a good habitat for birds.

・The specialists that exterminate birds with guns are aging. Therefore, their numbers are decreasing with each passing year.

・When the airports were constructed, the planners did not consider bird strike risk.

4.1.6 Land use around the airports

Table 4 shows the classification of land use around the airports. The correlation coefficient for farms is -0.41, meaning that as the farm area increases, the bird strike risk decreases. The correlation coefficient for a sea or lake is 0.27, meaning that as the area of the nearby sea or lake increases, the bird strike risk increases. In addition, since the correlation coefficient for the distance between

Table 4: Details of land use around airports.

No.	Name	Farm	Forest and field	Sea and Lake	town	airport
		(%)				(km)
4	Monbetsu	43.0	22.4	29.1	2.4	3.1
6	Memanbetsu	93.0	0	0	1.7	5.3
7	Nakashibetsu	90.2	0	0	5.9	3.9
9	Obihiro	90.3	0	0	0	9.7
18	Aomori	7.6	82.9	2.4	0	7.1
20	Oodate-Noshiro	62.6	32.7	0	1.6	3.1
21	Akita	2.9	91.3	0	0	5.7
22	Hanamaki	77.8	0	0	14.9	7.3
23	Shounai	78.2	0	17.3	0	4.5
24	Yamagata	70.8	0	0	25.7	3.5
28	Fukushima	54.6	39.3	0	2.4	3.8
29	Noto	0	96.2	0	0	3.8
43	Matsumoto	75.0	0	0	22.6	2.3
44	Toyama	30.3	0	0	66.6	3.1
48	Tottori	21.2	3.5	50.9	21.2	3.1
49	Kobe	0	0	77.4	18.1	4.5
51	Oki	0	32.0	59.6	4.8	3.6
52	Okayama	0	92.7	0.8	0	6.5
53	Izumo	32.6	24.4	34.0	6.7	2.3
55	Iwami	27.6	39.2	26.6	6.6	3.0
56	Yamaguchi-Ube	0	0	57.3	37.5	5.2
64	Tokushima	40.8	0	42.9	9.5	6.8
76	Fukue	75.6	20.8	1.4	0	2.2
79	Kagoshima	36.4	58.1	0	0	5.5
86	Saga	37.8	0	59.4	0	2.8
89	Kikai	30.6	5.9	57.1	5.6	0.8
90	Amami	27.7	12.8	53.2	2.1	4.2
91	Tokunoshima	28.1	1.4	60.1	8.4	2.0
92	Okinoerabujima	20.7	0	74.9	2.6	1.8
93	Yoron	25.5	0	71.3	1.7	1.5
103	Shimochijima	21.7	9.9	56.8	3.1	8.4
104	Miyako	59.9	9.1	9.2	17.5	4.3
105	Ishigaki	42.8	2.8	38.9	13.8	1.7
Correlation coefficient with number of BS		−0.41	0.07	0.27	0.16	0.07

the airport and the coastline is -0.32, it is clear that the existence of a sea or lake is a significant factor of bird strike risk.

4.2 Risk analysis

4.2.1 Field investigation

Based on observations from an area near the airport, the approach angles for the landing aircraft were approximately 2.5-4.5 degrees; takeoff angles were approximately 15-25 degrees. According to the experts from Tokyo Port Wild Bird Park, bird strikes typically occur at altitudes of 0-150 m, which is the altitude range that birds fly near Haneda Airport.

4.2.2 Risk analysis execution

Probability distributions were assumed for an airplane and a bird passing through a section of runway. For the airplane, the probability distribution was assumed to be a normal distribution curve, as shown in Figure 4. For the bird, the probability distribution was assumed to be a maximum extreme value distribution curve, as shown in Figure 4. If the altitude of an airplane were equal to the altitude of a bird in the same section, it was assumed that a bird strike occurred. In addition, the risk analysis assumed that the diameter of the airplane was 5.0 m.

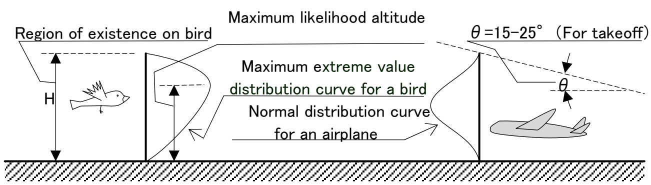

Figure 4: Probability curves for airplanes and birds.

For the airplane, the parameters that determined the normal distribution curve profile were the *minimum altitude*, *maximum altitude*, *average altitude*, and *standard deviation of altitude*; those values were assumed as listed in Table 5.

Table 5: Assumed parameters for the maximum extreme value distribution.

For Landing	Angle (in degree) (Field observation=3.95)			
	Minimum	Average	Maximum	
Angel of airplane's locus to ground	2.50	3.5	4.50	
Section	Altitude(m)			Standard Deviation (m)
Horizontal distance from landing point= 0m	0	2.50	5.00	4.0
Horizontal distance from landing point=500m	21.8	34.5	39.4	5.0
Horizontal distance from landing point=1000m	43.7	69.0	78.7	6.0
Horizontal distance from landing point=1500m	65.5	104	118	7.0
Horizontal distance from landing point=2000m	87.3	138	157	8.0
For Takeoff	Angle (in degree) (Field observation=18.6)			
	Minimum	Average	Maximum	
Angel of airplane's locus to ground	15.0	20.0	25.0	
Section	Altitude(m)			Standard Deviation (m)
Horizontal distance from landing point= 0m	0	2.50	5.00	4.0
Horizontal distance from landing point =150m	40.2	50.6	69.9	5.0
Horizontal distance from landing point = 300m	80.4	101	140	6.0
Horizontal distance from landing point = 450m	121	152	210	7.0

For the bird, the parameters that determined the maximum extreme distribution curve profile were the *altitude range* and *maximum probable altitude*. Twenty-five cases were chosen based on the experts' suggestion that small birds fly at altitudes less than about 80 m. Therefore, in this study, we conducted the simulation under the condition for small birds; details of the 25 cases are shown in Table 6.

Table 6: Assumed parameters for the maximum extreme value distribution.

Region of existence on bird	Maximum likelihood altitude (m)				
	H/4	H/3	H/2	2H/3	3H/4
Altitude =0 to 40m	10.0	13.3	20.0	26.7	30.0
Altitude =0 to 50m	12.5	16.7	25.0	33.0	37.5
Altitude =0 to 60m	15.0	20.0	30.0	40.0	45.0
Altitude =0 to 70m	17.5	23.3	35.0	46.7	52.5
Altitude =0 to 80m	20.0	26.7	40.0	53.3	60.0

Although there were about 371,000 takeoffs and landings in 2010, that number is expected to increase to about 447,000 in the near future. Therefore, for the Monte Carlo simulation, the number of takeoffs and landings was assumed to be 55,857 per runway (=447.000 times/4 runways).

Table 7: Risk of bird strike during takeoff.

Range of altitude on bird (m)	Maximum llikelihood value (m)	Risk of BS occurrence for takeoff (%)			
		Averaged altitude of airplane=0m, Horizontal distance after takeoff=0m	Averaged altitude of airplane=50.6m, Horizontal distance after takeoff=150m	Averaged altitude of airplane=101.1m, Horizontal distance after takeoff=300m	Averaged altitude of airplane=151.7m, Horizontal distance after takeoff=450m
0 - 40	10.0	7	0	0	0
	13.3	6	0	0	0
	20.0	4	0	0	0
	26.7	2	0	0	0
	30.0	2	0	0	0
0 – 50	12.5	5	2	0	0
	16.7	7	2	0	0
	25.0	2	4	0	0
	33.0	1	5	0	0
	37.5	0	6	0	0
0 - 60	15.0	4	4	0	0
	20.0	3	5	0	0
	30.0	1	8	0	0
	40.0	0	11	0	0
	45.0	0	14	0	0
0 - 70	17.5	4	5	0	0
	23.3	2	6	0	0
	35.0	0	9	0	0
	46.7	0	12	0	0
	52.5	0	12	0	0
0 - 80	20.0	3	3	0	0
	26.7	1	6	0	0
	40.0	0	9	0	0
	53.3	0	12	0	0
	60.0	0	11	0	0

4.3 Simulation results

From the simulation results provided in Tables 7 and 8, a high bird strike risk can be seen. Note that the bird was assumed to exist in the runway section in every calculation and the simulation did not consider three-dimensional effects. However, Tables 7 and 8 can be considered qualitative expressions of bird strike risk.

Table 8: Risk of bird strike during landing.

Range of altitude on bird (m)	Maximum llikelihood Value (m)	Risk of BS occurrence for landing (%)				
		Averaged altitude of airplane=0m, Horizontal distance before landing=0m	Averaged altitude of airplane=34.5m, Horizontal distance before landing=500m	Averaged altitude of airplane=69.0m, Horizontal distance before landing=1000m	Averaged altitude of airplane=103.6m, Horizontal distance before landing=1500m	Averaged altitude of airplane=138.1 m, Horizontal distance before landing=2000 m
0 - 40	10.0	7	9	0	0	0
	13.3	6	10	0	0	0
	20.0	4	12	0	0	0
	26.7	2	15	0	0	0
	30.0	2	16	0	0	0
0 – 50	12.5	6	9	0	0	0
	16.7	4	10	0	0	0
	25.0	2	12	0	0	0
	33.0	1	14	0	0	0
	37.5	0	15	0	0	0
0 - 60	15.0	4	9	0	0	0
	20.0	3	10	0	0	0
	30.0	1	12	0	0	0
	40.0	0	14	1	0	0
	45.0	0	15	1	0	0
0 - 70	17.5	4	8	1	0	0
	23.3	2	9	2	0	0
	35.0	0	10	3	0	0
	46.7	0	9	5	0	0
	52.5	0	7	7	0	0
0 - 80	20.0	3	9	2	0	0
	26.7	1	9	3	0	0
	40.0	0	10	5	0	0
	53.3	0	6	10	0	0
	60.0	0	3	12	0	0

4.3.1 Takeoff case

As shown in Table 7, a high bird strike risk exists after takeoff when the airplane travels 150 m in the horizontal direction and is at an altitude of 30 to 60 m.

4.3.2 Landing case

As shown in Table 8, a high bird strike risk exists on approach when the airplane is 500 m in the horizontal direction from touchdown and at an altitude of 20 to 40 m. Also, in comparing takeoffs and landings, the bird strike risk is higher during landing than during takeoff because the airplane remains in the bird altitude range for a longer period of time during landing (due to the shallow approach angle).

4.4 Bird strike countermeasures

It is clear that bird strikes tend to occur immediately after takeoff and before landing. Therefore, for takeoff, acoustic bird deterrents should be installed along the runway at adequate intervals. For landing, radar systems should be able to detect birds near the airport; if the birds can be detected by radar, bird strikes should be preventable by the air traffic control system.

5 Conclusions

Precautions were proposed for planners to consider when opening a new airport. Using questionnaires, officials from airports around Japan provided data on airport conditions, usage, and bird strike history. From this data, it is clear that bird strike occurrence depends highly on the proximity and size of a sea or lake. Therefore, airport planners should consider bird strike risk if the airport will be constructed near a sea or lake.

A risk analysis was conducted using a Monte Carlo simulation of Tokyo's Haneda Airport as an example. Probability distributions were assumed for an airplane and a bird passing through a section of runway. The bird strike risk was shown to be higher for landings than for takeoffs. Furthermore, for landings, the bird strike risk tends to be high when the airplane is within 500 m (in the horizontal direction) of touchdown. Bird strike countermeasures were suggested for both takeoff and landing: For takeoff, acoustic bird deterrents should be installed along the runway at adequate intervals; for landing, radar should detect birds around the runway, and bird strikes should be prevented by the air traffic control system.

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