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COVID-19 Reverse Prediction and Assessment on the *Diamond Princess* Cruise Ship

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As of July 21, 2020, the coronavirus SARS-CoV-2 had spread to almost all countries around the world and caused more than 14.8 million confirmed cases, owing to its high transmissibility and fast rate of spread. Of the infected locations, the *Diamond Princess* cruise ship is special in that it is an isolated system with a population highly concentrated in a limited space, providing particularly favorable conditions for the transmission of the novel coronavirus-associated pneumonia, COVID-19. The Japanese government's emergency measures for controlling the spread of COVID-19 on the cruise ship have also been questioned. In this paper we develop a homogeneous mixed difference system to describe the mechanism of transmission of COVID-19 on the cruise ship, reverse-predict the epidemic transmission trend from January 20 to February 20, 2020, including the daily number of infected people and the peak time of infection, estimate the range of the basic reproduction number of virus transmission on the cruise ship, and assess the effects of prevention and control measures. It is concluded that the isolation of people, along with rapid and comprehensive detection of infections, play an important role in controlling the epidemic. In fact, the Japanese government's emergency measures did have a certain effect on limiting the spread of COVID-19, but the number of infected people could have been reduced by at least 60% if all personnel on the cruise ship had been tested and isolated promptly as early as February 5.

Keywords: COVID-19, *Diamond Princess*, difference equation, reverse prediction, reproduction number, measures assessment, infection scale

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1. INTRODUCTION

Since December 2019 a new coronavirus pneumonia, named COVID-19, has spread menacingly quickly and invaded more than 200 countries, infecting over 14.8 million people and causing more than 600,000 deaths by July 21, 2020. Among the infected places, the *Diamond Princess* cruise ship is a special case; the course of development of the epidemic on the ship is shown in **Figure 1**. On January 20, the *Diamond Princess* departed from Yokohama, Japan, and a passenger from Hong Kong embarked. The passenger disembarked in Hong Kong on January 25 and was confirmed to be infected with SARS-CoV-2 on February 1. The *Diamond Princess*, which was scheduled to return to Yokohama on February 5, arrived ahead of time on February 4 and was subjected to quarantine and inspection. According to requirements of the Ministry of Health, Labor and Welfare of Japan,

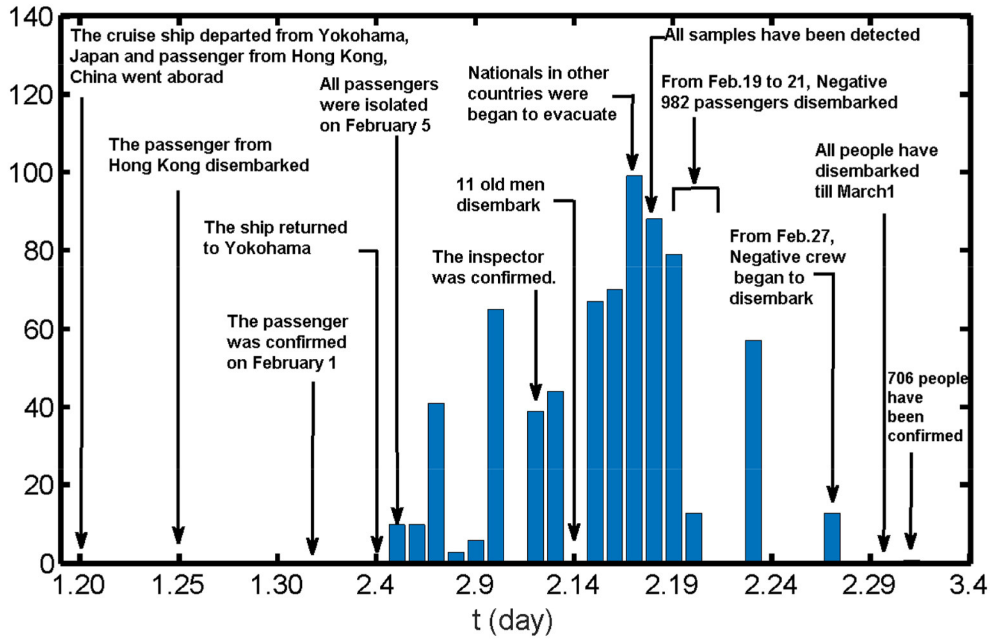

FIGURE 1 | The course of development of the COVID-19 epidemic on the *Diamond Princess* cruise ship.

from February 5 all passengers on the *Diamond Princess* had to be isolated in their cabins for 14 days. During the quarantine period, passengers and crew were tested in batches irregularly, and individuals confirmed to be positive for COVID-19 were to disembark for treatment at designated institutions in Japan. With the comprehensive implementation of systematic detection starting from February 14, all testing work was completed on February 18. Meanwhile, from February 17, other countries began to evacuate their nationals on chartered flights. From February 19, passengers who tested negative and in whose room there were no confirmed cases were allowed to disembark. From February 27, the crew of the cruise ship began to disembark and were sent to Saitama prefecture and Hikari city in Japan to be isolated for 14 days. By March 1, all people had disembarked from the cruise ship. Eventually, a total of 721 on the *Diamond Princess* were reported to be infected with SARS-CoV-2.

During the initial phase of infection on the cruise ship, the Japanese government did not pay enough attention to the outbreak and did not test, survey, evacuate, or isolate people in a timely fashion, but only asked passengers to isolate themselves in their cabins, and continued to allow air to be circulated on the ship through the central air-conditioning system. Siqi Sun, a lecturer at Shanghai Maritime University and the author of the book *Cruise Tourism Law Thesis*, has said that this is the most complex crisis in the history of cruises since the *Titanic* event in 1909 [1]. In the present work, we aim to use mathematical methods [2] to elucidate the mechanism of COVID-19 transmission on the *Diamond Princess* cruise ship, and thus provide a theoretical basis for guidance on epidemic prevention and control in similar closed systems.

At the early stage of the epidemic on the *Diamond Princess*, information about the outbreak was limited to daily detected and confirmed cases. However, the sampling method and the proportion of inspected samples were irregular, so it is difficult to capture the pattern of the epidemic during the early stage, let alone use it to predict the later development of the epidemic. However, by May 2020 all cases of infection had been confirmed. Therefore, based on the final cumulative number of confirmed cases, the transmission trend of the epidemic from January 20 to February 20 can be reverse-predicted and evaluated. For this purpose, considering that the mode of contact between people on the ship is close to uniform mixing, we derive a homogeneous mixing difference equation to describe the transmission mechanism of COVID-19 on the ship, with the goal of understanding the characteristics of epidemic transmission in a confined space. In addition, we estimate the number of people infected by the Hong Kong passenger from January 20 to January 25, the number of people who had been infected by February 5 when isolation measures were put in place, and the peak time and peak value of the epidemic on the cruise ship. Moreover, we estimate the basic reproduction number of the spread of COVID-19 on the ship. Finally, we assess the effects of the isolation measures taken by the Japanese government.

2. MATERIALS AND METHODS

2.1. Materials

We study the infection status of 3,711 people on the cruise ship, including 2,666 passengers and 1,045 crew members, from January 20 to February 20. The numbers of detected and confirmed cases are shown in **Table 1** [1, 3–5], where detected

TABLE 1 | Detected and confirmed cases out of 3,711 people on the *Diamond Princess*.

Date	Cumulative number of detected cases	Cumulative number of confirmed cases	Number of people disembarking
February 5	31	10	10
February 6	102	20	20
February 7	202	61	41
February 8	208	64	3
February 9	336	70	6
February 10	439	135	65
February 11	439	135	0
February 12	492	174	39
February 13	713	218	44
February 14	714	218	11
February 15	930	285	67
February 16	1,219	355	70
February 17	1,723	454	437
February 18	2,404	542	88
February 19	3,011	621	522
February 20	/	634	522
February 27	/	705	/
March 3	/	706	/
	/	721 (final number)	/

cases refer to individuals who had taken a nucleic acid test of which the result is uncertain (may be negative or positive), and confirmed cases refer to individuals whose tests came back positive.

2.2. Prerequisites

We assume that the first case on the cruise ship is the passenger from Hong Kong, who boarded the ship on January 20 and disembarked on January 25.

We also assume that everyone on the cruise ship has the same contact number per day, denoted by $C(t)$. Since the Japanese government began to test and isolate all individuals on the cruise ship from February 5, the model is divided into two stages: (i) January 20 to February 4, and (ii) February 5 to February 20. The average number of close contacts per person per day is denoted by C_1 during the first stage and by C_2 during the second stage.

2.3. Dynamical Model

We take January 20 to be the initial time, denoted by $t = 1$. At time t, the number of infected but not confirmed (INC for short) is denoted by $I(t)$. As given in **Figure 2**, the variation with time is given by

$$\begin{aligned}&\text{number of INC at time } t+1 = \text{number of INC at time } t\\&\quad + \text{number infected by the Hong Kong passenger at time } t\\&\quad + \text{number infected by other passengers at time } t\\&\quad - \text{number of newly confirmed cases at time } t.\end{aligned}$$

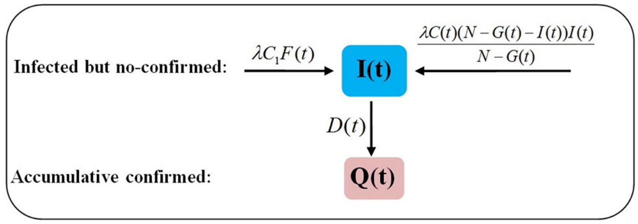

FIGURE 2 | Transfer diagram for the dynamical transmission of COVID-19 among subpopulations.

Let $F(t)$ be the number of imported infected persons at time t. It is assumed that the Hong Kong passenger is the only imported case. Then $F(t) = 1$ from January 20 to January 25, i.e., for $1 \leq t \leq 6$, and $F(t) = 0$ for $t > 6$. The daily number of close contacts of the Hong Kong passenger is C_1, and let λ be the probability of another individual being infected by the passenger after close contact. Then the number of people infected by the Hong Kong passenger at time t is $\lambda C_1 F(t)$.

At time t, for all infected individuals except the Hong Kong passenger, the close contact number per person per day is $C(t)$. The proportion of uninfected (i.e., susceptible) people is $\frac{N-G(t)-I(t)}{N-G(t)}$, where N is the total number of people on the cruise ship on February 5, $G(t)$ is the cumulative number of people who have disembarked, and $N - G(t)$ is the total number of people remaining on the cruise ship at time t. Hence, the number of infected people caused by one infected individual at time t is $\frac{\lambda C(t)(N-G(t)-I(t))}{N-G(t)}$, and the number of infected people caused by all infected individuals at time t is $\frac{\lambda C(t)(N-G(t)-I(t))}{N-G(t)} I(t)$. The number of newly confirmed cases at time t is denoted by $D(t)$. The cumulative number of confirmed cases at time t is denoted by $Q(t)$. The cumulative number of infected cases at time t is denoted by $A(t)$.

Hence we have the system of equations

$$\begin{aligned}I(t+1) &= I(t) + \lambda C_1 F(t) + \frac{\lambda C(t)(N-G(t)-I(t))I(t)}{N-G(t)} - D(t),\\A(t+1) &= A(t) + \lambda C_1 F(t) + \frac{\lambda C(t)(N-G(t)-I(t))I(t)}{N-G(t)},\\Q(t+1) &= Q(t) + D(t),\end{aligned} \tag{1}$$

where

$$F(t) = \begin{cases} 1 & \text{for } t \leq 6,\\ 0 & \text{for } t > 6\end{cases}$$

and

$$C(t) = \begin{cases} C_1 & \text{for } t < 17,\\ C_2 & \text{for } t \geq 17.\end{cases}$$

2.4. Parameter Values

In this subsection, we use real data (see **Table 1**) to estimate the parameter values in model (1), which are given in

TABLE 2 | Values of parameters and variables in model (1).

Parameter	Meaning	Value	Confidence interval	Source
$D(t)$	Daily new number of confirmed cases at time t	See **Table 1**	/	Real data
$G(t)$	Daily cumulative number of people disembarking at time t	See **Table 1**	/	Real data
λ	Transmission probability per contact	0.05	/	(a)
C_1	Contact number per person per day before February 5	9.2472 (Case I)	[8.7184, 9.7760]	(b)
C_2	Contact number per person per day after February 5	1.5013 (Case I)	[0.8685, 2.1341]	(b)
C_1	Contact number per person per day before February 5	6.4386 (Case II)	[6.4301, 6.4472]	(b)
C_2	Contact number per person per day after February 5	6.4386 (Case II)	[6.4301, 6.4472]	(b)
N	Total number of staff on ship	3, 711	/	Real data
$I(0)$	Initial number of infected individuals	0	/	Real data
$A(0)$	Initial number of cumulative infected individuals	0	/	Real data
$Q(0)$	Initial number of cumulative confirmed individuals	0	/	Real data
$A(32)$	Theoretical number of cumulative infected individuals on February 20	/		
$\hat{A}(32)$	Actual number of cumulative infected individuals on February 20	/	[720, 760]	(c)

Table 2. We describe the process of parameter estimation, which is implemented using the function `fminsearch` in the optimization toolbox of MATLAB.

(a) The meaning of λ is the transmission probability per contact. We estimate its value by combining information from references [6–8], which studied the spread of the epidemic in Wuhan city, in Shanxi province, and on the *Diamond Princess*, respectively. In Zhang et al. [6] the transmission probability per contact was found to be 0.0149; in Xue et al. [7] the values 0.01597 and 0.04644 were given; and Liu et al. [8] provided a range of 0.001–0.2 for the transmission probability per contact. Based on these estimates, here we take the value of λ to be 0.05.

(b) We use the least-squares estimation method to obtain the values of C_1 and C_2 in Case I and the value of $C_1 = C_2$ in Case II (see section 3 for description of the cases) by fitting the theoretical value of $A(32)$ in model (1) to the actual cumulative number of infected individuals, denoted by $\hat{A}(32)$. Individuals on the cruise ship were isolated, with each passenger staying in their own cabin. Each cabin on the *Diamond Princess* can accommodate four people [9], so we suppose that the average number of people in each cabin is 3. As for the crew, from February 5 they took meals in the canteen in turn, and the dining room table can accommodate 12 people. Therefore, we assume that the average contact number for each crew member is 12. The proportions of passengers and crew on the ship were 71.8 and 28.2%, respectively, so we calculate that the average contact number per person per day for passengers and crew is between 5 and 6.

(c) According to Japan's health ministry bulletin, all individuals on the ship had been tested and had disembarked by March 1, and the total number of officially reported confirmed cases is 721 [5]. Besides those, 38 passengers tested negative when disembarking but were later confirmed to be positive [10, 11]. Considering that some of these people may have become infected on their way back home, we estimate that on February 20 the actual cumulative number of infected individuals, $\hat{A}(32)$, was between 720 and 760.

3. RESULTS

The isolation measures taken by the Japanese government have been controversial, and the actual infection situations before and after the measures were imposed are not clear. In this section, we reverse-predict the infection on the cruise ship in two scenarios.

3.1. Case I

In this scenario it is assumed that the isolation measure is effective by itself, and that circulating air through the central air-conditioning system does not cause spread of the virus. Under isolation, close contacts of passengers were restricted to their cabin mates, and close contacts of crew members were limited to those dining together. Based on the model and parameter values, by calculating $\frac{\lambda C(t)(N-G(t)-I(t))}{N-G(t)}I(t)$ and $A(t)$ we can estimate the new daily number and cumulative number of infected people from January 20 to February 20; these values are reported in **Figure 3** and **Table 3**.

From **Figure 3A** we observe that the peak time of the epidemic in this case is from February 5 to February 15. As of February 20, there were still 100 infected but not confirmed individuals on the ship. By comparing the red dots with the black solid line, we can see that the number of confirmed cases was far less than the number of infected people before February 14. The comprehensive and systematic testing from February 14 led to a rapid fall in the number of infected persons, and the cumulative number of infected people and the total number of confirmed cases gradually became closer. So we can see that isolating people and conducting comprehensive testing play important roles in epidemic control. From **Table 3** we also see that there would have been about 258 ([188, 328]) infected individuals on February 5 when the cruise ship was isolated. It can be concluded that because the Japanese government did not pay enough attention to the epidemic at the initial stage and did not carry out comprehensive testing on all people onboard in time, the final proportion of infected reached nearly 20%. If measures had been taken for the *Diamond Princess* as promptly as for the *Costa Selena* cruise ship, which carried 4806 passengers

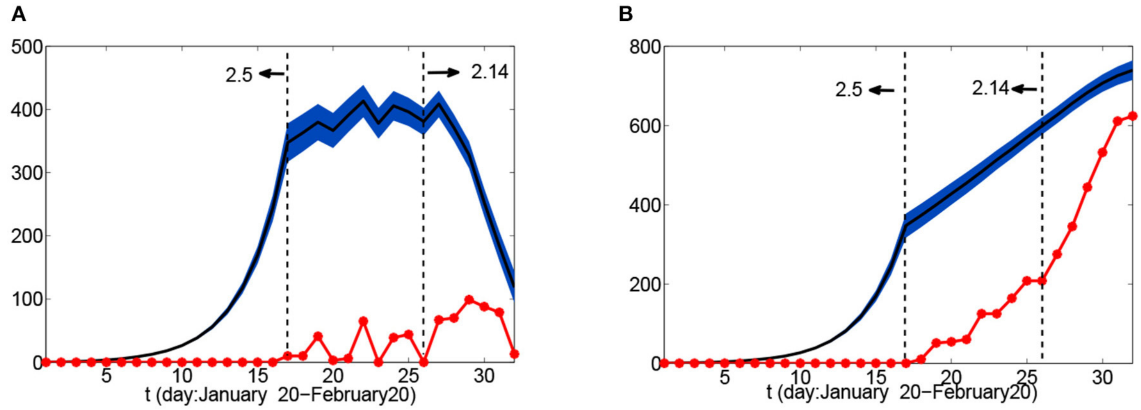

FIGURE 3 | Number of infected people as a function of time from January 20 to February 20 in Case I: (A) daily new number of infected cases; (B) daily cumulative number of infected cases. Red dots represent actual confirmed numbers; black dotted lines indicate critical time nodes; the black solid line represents the theoretical mean value of the number of infected, $\frac{\lambda C(t)(N-G(t)-I(t))}{N-G(t)}I(t)$ in (A) and $A(t)$ in (B); the blue area represents the interval of 10,000 times deduction results.

TABLE 3 | Reverse-predicted infection size and peak in Cases I and II.

Case	Number of people infected by Hong Kong passenger	Infected population on February 5	Infected population on February 20	Peak time of infection
I	2.7742 ([2.6155,2.9328])	257.9222 ([187.9917,327.8528])	109.0139 ([96.4057,121.6221])	February 5 to February 15
II	1.9316 ([1.9290,1.9341])	52.9066 ([52.6305,53.1826])	119.5218 ([94.9011,144.1424])	February 15 to February 16

and crew members and for which the Chinese government spent 1 h formulating the response plan, 4 h conducting the sampling work, 5 h producing the test results, and 24 h overall completing the detection, evacuation, and resettlement work [12], the number of infected on the *Diamond Princess* could have been reduced by at least 60–70%. This shows that the effect of non-pharmaceutical interventions on controlling the spread of COVID-19 is very considerable [13].

The reproductive number (including the basic reproductive number, or the effective reproductive number) is an index that measures the number of infected people caused by a single infected individual during the infection period. In Case I, the basic reproductive number can be estimated based on the Hong Kong passenger infecting about 3 (2.7742) persons from January 20 to January 25 by the sum $\sum_{t=1}^{6} \lambda C_1 F(t)$, which can be taken as the reproductive number of the Hong Kong passenger. Based on reference [14], the incubation period of COVID-19 is 3–5 days, so we assume that it will take 3–5 days from showing clinical symptoms to becoming a confirmed case on the cruise ship. Then the infection period is assumed to be 6–10 days. Besides, according to reports of the National Institute of Infectious Diseases of Japan, as of February 18 the percentage of infected but symptomless samples among 2,404 respiratory tract specimens was as high as 48%. Assume that the average time between being infected and being confirmed for asymptomatic infection is 10–15 days. Combining symptomatic and asymptomatic infections, we estimate the basic reproduction number of the cruise ship to be 3.66–5.54; see **Table 4**. For Wuhan city in Hubei province, China, which also became an isolated system after sealing, the basic reproduction number is 1.4–4.0 [15, 17, 19, 20]. For China as a whole, the basic reproduction number is 3.51–4.05 [21]. The basic reproduction number of the cruise ship is larger, which may be due to the higher population density, a more enclosed space, a higher percentage of asymptomatic infections, and delayed testing for all individuals.

TABLE 4 | Comparison of the basic reproduction number in different regions.

Region	Basic reproduction number	Source
Diamond Princess cruise ship	3.58–5.63	Case I
	2.54–3.99	Case II
Wuhan city	1.5–2.5	WHO
	1.47–2.59	[12]
	2.47–2.86	[14]
	3.6–4.0	[15]
	1.16–1.48	[16]
	2.2	[17]
Hunan province	1.34	[18]
Shandong province	1.71	[18]
Shenzhen city	1.08	[18]
China	3.51–4.05	[19]

3.2. Case II

Japan's emergency measures, which kept passengers isolated in cruise cabins but continued to circulate air through central air-conditioning, was questioned by many experts. Assume

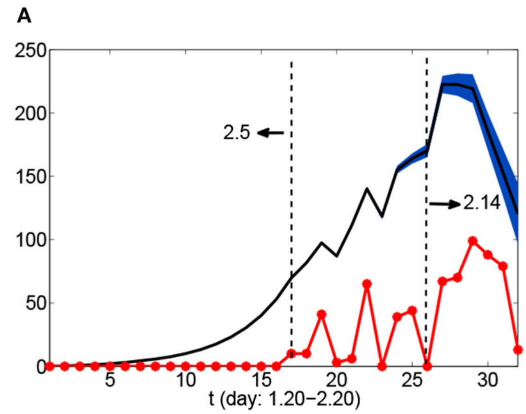

FIGURE 4 | Number of infected people as a function of time from January 20 to February 20 in Case II: (A) daily new number of infected cases; (B) daily cumulative number of infected cases. Red dots represent actual confirmed numbers; black dotted lines indicate critical time nodes; the black solid line represents the theoretical mean value of the number of infected, $\frac{\lambda C(t)(N-G(t)-I(t))}{N-G(t)} I(t)$ in (A) and $A(t)$ in (B); the blue area represents the interval of 10,000 times deduction results.

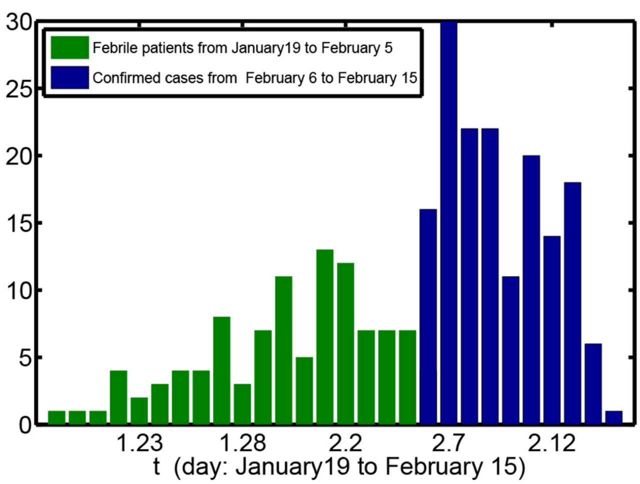

FIGURE 5 | Number of cases plotted against time. The green bars show the number of febrile patients and the blue bars the number of confirmed COVID-19 cases with reported onset times.

that after isolation, the close contact number of each person does not change due to circulation of air in the central air-conditioning system, that is, $C_1 = C_2$. Similarly to Case I, based on the model and parameter values we can calculate the new number and cumulative number of infected people from January 20 to February 20, as shown in **Figure 4** and **Table 3**. By inspection of **Figure 4A**, the infection peak time is from February 15 to February 16. Although the quarantine measure was imposed on February 5, the upward trend in the number of infections remained largely unchanged. Comparing the red dots with the black solid line in **Figure 4A**, we see that the comprehensive and systematic testing which started on February 14 resulted in a rapid decline in the number of infected people after February 17. We also find that there were about 53 infected individuals on February 5 when the cruise ship was isolated. If the Japanese government had completed response measures, such as detection, evacuation, and resettlement work as quickly as was done for the *Costa Selena*, the number of infected on the *Diamond Princess* could have been reduced by at least 90%. In Case II, it can be estimated that the Hong Kong passenger infected about two persons (1.9316) from January 20 to January 25. In this case, then, we estimate the basic reproduction number on the cruise ship to be 2.55–3.99.

4. DISCUSSION AND CONCLUSION

In this article we have used a mathematical dynamical model to reversely deduce, in two hypothetical cases, the number of people infected with COVID-19 on the *Diamond Princess* cruise ship from January 20 to February 20, 2020, the peak time of infection, the number of the infections caused by the Hong Kong passenger, and the basic reproduction number, information which can provide the theoretical basis for understanding the spread of the epidemic and developing effective control measures. The results reported in this paper demonstrate that a dynamical model which incorporates a transmission mechanism can be a very useful method for predicting the spread of a disease, especially when actual data are scarce [22–25].

Although the premises of the two cases are different, it can be deduced that quarantining populations and conducting comprehensive testing play an important role in control of the epidemic, and that detection of cases needs to be timely.

According to the report published by the National Institute of Infectious Diseases of Japan, as of February 18, 2,404 samples on the *Diamond Princess* cruise ship had been tested (including samples for double detection), and 531 cases were confirmed to be positive for COVID-19. Of these, 33 cases showed symptoms before February 6, 151 showed symptoms on or after February 6, and 255 (48%) were asymptomatic. Combining the time of diagnosis of 79 patients with fever before February 6 (only 33 of which were confirmed cases) with the onset time of 151 confirmed cases after February 6, we obtain **Figure 5**. As can be seen from the figure, the infection peak was reached on February 7. Comparing with **Figures 3A**, **4A**, Case I seems closer to the actual situation, indicating that the role of central air-conditioning in transmission of the disease is relatively small, and that the isolation intervention adopted by the Japanese government had a certain impact on reducing the transmission of the virus from one person to another.

By our analysis, we estimate the reproduction number associated with the Hong Kong passenger to be between 1.9290 and 2.9328. In fact, the time period between the date of infection and date of confirmation for other persons on the cruise ship is irregular and cannot be determined, so the period of infection cannot be determined and hence the basic reproduction number cannot be found accurately. Nevertheless, we can give a general range [2.54, 5.63]. If the Japanese government had completed response measures for the *Diamond Princess*—including detection, evacuation, and resettlement work—as promptly as was done for the *Costa Selena* cruise ship (within 24 h), the number of infections on the *Diamond Princess* could have been reduced by at least 60%. In this respect, the response measures taken for the *Costa Selena* in Tianjin Port provide a positive paradigm. Moreover, 38 *Diamond Princess* passengers who tested negative on the ship were confirmed to have the disease after they disembarked, indicating that the nucleic acid test had certain errors and led to a proportion of infected people not being detected and thus becoming a potential source of risk for other regions. Therefore, the accuracy of the testing method should also be improved.

DATA AVAILABILITY STATEMENT

All datasets presented in this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

JZ, G-QS, ML, and ZJ conceived and designed the experiments. JZ and G-QS performed the experiments. JZ, G-QS, and ML developed the dynamical model. RG, XP, and HR collected and analyzed the data. JZ, HR, XP, and RG analyzed the data. JZ, G-QS, and ZJ wrote the manuscript. All authors contributed to the article and approved the submitted version.

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