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The Impact of Population Migration on the Spread of COVID-19: A Case Study of Guangdong Province and Hunan Province in China

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On the eve of the Spring Festival in 2020, the coronavirus disease 2019 (COVID-19) was reported. Subsequently, the Chinese government at all levels took emergency measures to control the spread of COVID-19 among people. Guangdong and Hunan are large population floating provinces. The spread of COVID-19 is affected by population migration. Before the Spring Festival, Guangdong and Hunan Provinces dominated population export and import, respectively; after the Spring Festival, the trend of population flow was reversed by the resumption of work. Taking Guangdong and Hunan as examples, we establish a three-stage dynamical model to study the impact of population migration on the spread of COVID-19. The result reveals that Guangdong Province mainly emigrated the population and the scale of infection was reduced before the Spring Festival. However, the situation in Hunan Province was just the opposite. After the Spring Festival, work resumption was taking place across China and the migration of Guangdong may cause a second outbreak of the epidemic. While people in Hunan leave the province to work, the migration of population will have little effect on the spread of COVID-19.

Keywords: COVID-19, dynamical modeling, migration, basic reproduction number, work resumption

1. INTRODUCTION

At the end of 2019, unknown pneumonia was reported. The World Health Organization (WHO) officially named the new coronavirus as COVID-19 on February 11, 2020 [1, 2]. The main transmission routes of COVID-19 are direct transmission, aerosol transmission, and contact transmission [3]. Early, Li et al. analyzed the data of 425 confirmed cases in Wuhan to determine the epidemiological characteristics of NCIP [4]. As the time of the outbreak is approaching the Spring Festival, passenger traffic from Wuhan to all parts of the country was large, which caused the rapid spread of COVID-19. In order to control the epidemic effectively, the Chinese government took the lockdown strategy in Wuhan on January 23 [5]. Everyone who came from Hubei Province has to be registered and then quarantined at home for 14 days. The flights, railways, and highways taken by people from Wuhan were closely followed up and announced in detail after registration. In order to control the spread of COVID-19, the government took a series of measures, such as prohibiting all transport in and out [6, 7] and disinfecting and taking body temperature in public places. For individuals, people must wear their own masks when going out.

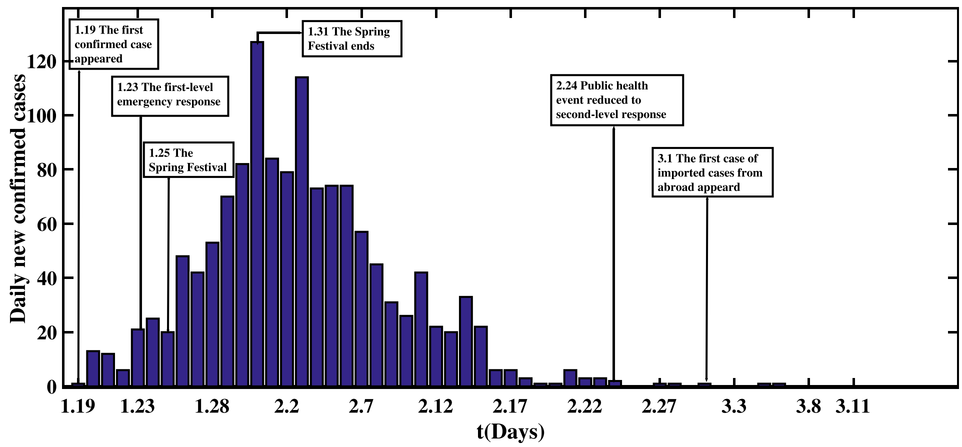

FIGURE 1 | Transmission scheme of COVID-19 in Guangdong Province. Guangdong Province launched the first-level response to major health incidents on January 23 and the Spring Festival ends on January 31.

At present, the epidemic is still spreading globally. Many research teams have been studying the impact of COVID-19 transmission in real time. The study of dynamical modeling to predict the epidemic rule plays an important role in disease control [8–11]. Typically, Li et al. analyzed the impact of different lockdown time in Wuhan on the transmission of COVID-19 in Shanxi Province [12]. Tang et al. focused on the time to resume work and assessed the risk of the epidemic [13–15]. Furthermore, Huang et al. predicted the trend of COVID-19 and calculated the parameters of this epidemic [16]. Moreover, lots of scholars established dynamical modeling to analyze the influence of different quarantine measures on the spread of COVID-19 [17–19]. For example, Gao et al. established dynamical modeling showing that the epidemic was controlled by reducing the contact rate [20]. Some works were dedicated to assessing the effectiveness of epidemic prevention and control measures [21–23]. Meanwhile, great academics have discussed the issue of media raising awareness of epidemic prevention and control [24, 25].

For the provinces with a large flow of people, Guangdong and Hunan naturally attract great attention from society. Compared with other provinces in China, Guangdong Province has the largest number of migrant people. We collected data on reported confirmed cases of COVID-19 in Guangdong from January 19 to March 11 released by the Health Commission of Guangdong Province [26]. **Figure 1** illustrates the time series of confirmed COVID-19 cases in Guangdong Province. On January 19, the National Health Commission verified the first confirmed case of pneumonia with imported COVID-19 infection in Guangdong Province. Guangdong Province initiated the first-level emergency response on January 23. **Figure 1** shows that the peak of daily new confirmed cases is 127 cases on January 31, and the epidemic will disappear at the end of February. Based on Baidu migration data [27], **Figure 2** indicates the number of migrant people in Guangdong and Hunan around the Spring Festival proportion. Before the Spring Festival, most of the people of Hunan Province immigrated from Guangdong, Hubei, and Jiangxi Provinces on a large scale, among which Guangdong Province had the largest immigration population accounting for more than half of the total. However, the main emigration population of Guangdong Province flowed to Hunan Province, Guangxi Zhuang Autonomous Region, and Jiangxi Province. After the Spring Festival, work resumption was taking place across China. Most of the emigrants from Hunan Province went to work in Guangdong Province. At this time, the trend of population flow in the two provinces was opposite to that before the Spring Festival.

In order to reflect the COVID-19 variations and describe the impact of population migration on the spread of COVID-19, we establish the corresponding dynamical modeling in three different time periods around the Spring Festival and calculate the basic reproduction number for each stage. Using the actual data published by the Health Commission, the parameters were estimated and 95% confidence interval was obtained to verify the rationality of the dynamical modeling [26, 28]. Finally, we draw practical conclusions based on dynamic modeling, which provides some help for resuming work.

We conduct a detailed study of immigration and emigration of population, which is helpful to the prevention and control of areas with large population flows all over the world. At present, there are few teams to study the spread of COVID-19 in provinces. We not only consider the control characteristics in different provinces but also combine the features of the Spring Festival to establish multiple-stage dynamical modeling on the time scale, which can more accurately predict the development trend of the epidemic.

2. METHODS

2.1. Data Sources

In our study, we use Baidu migration data to estimate the immigration and emigration rates of Guangdong and Hunan Provinces around the Spring Festival [27]. In addition, we used

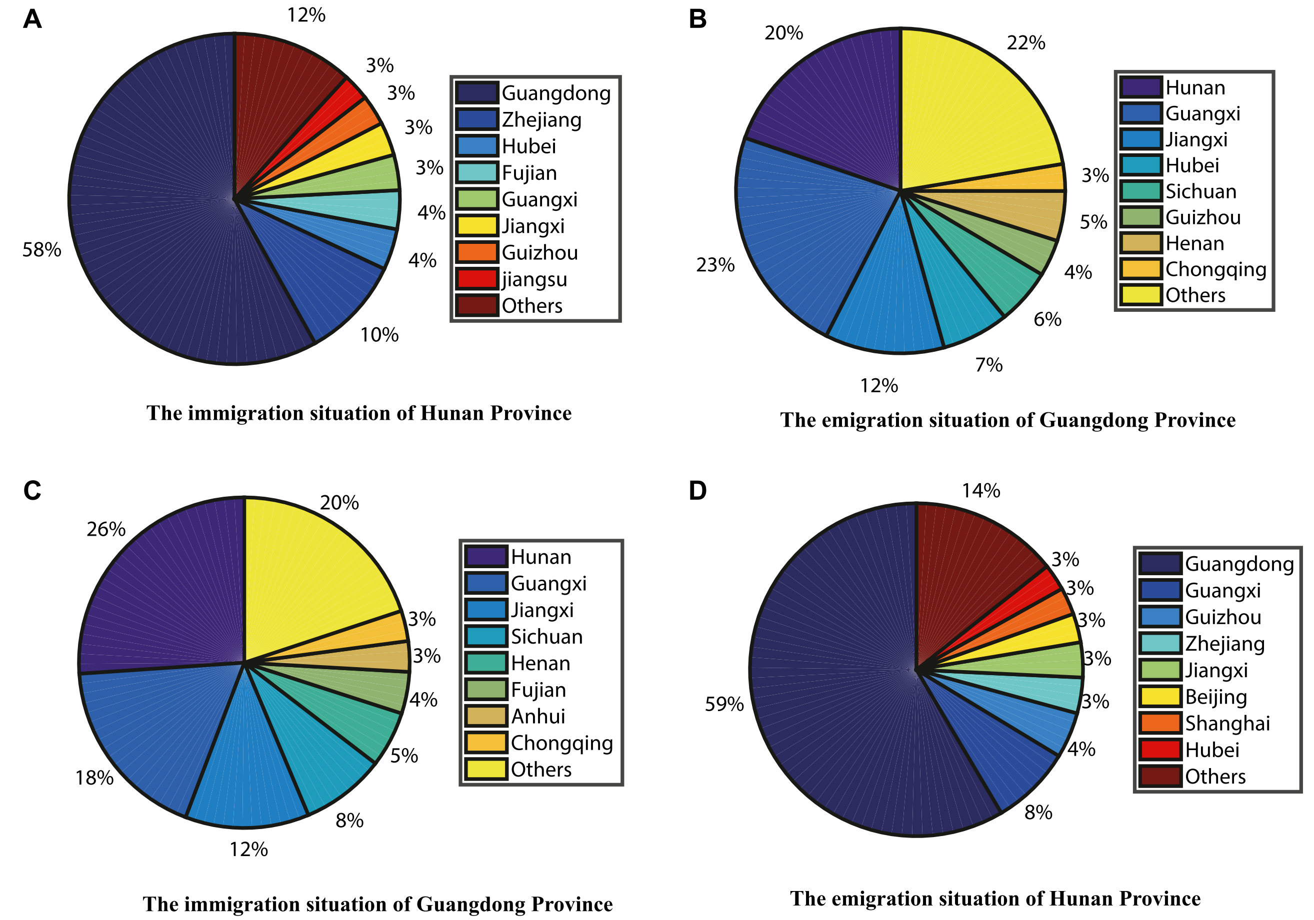

FIGURE 2 | Migration of population in Hunan Province and Guangdong Province [27]. **(A)** The immigration situation of Hunan Province before the Spring Festival. **(B)** The emigration situation of Guangdong Province before the Spring Festival. **(C)** The immigration situation of Guangdong Province after the Spring Festival. **(D)** The emigration situation of Hunan Province after the Spring Festival.

the information released by Guangdong and Hunan Provincial Health Commissions to collect the number of cumulative and daily new confirmed COVID-19 cases [26, 28]. According to the information released by the National Bureau of Statistics, we obtained the number of permanent residents in Guangdong and Hunan Provinces at the end of this year [29].

2.2. Dynamical Modeling Construction and Analysis

Based on the knowledge of COVID-19, it is necessary to establish dynamical modeling to further understand the transmission mechanism [30–33]. Most infectious diseases are studied in three parts: susceptible population, transmission route, and infected population [34–37]. According to the characteristics of COVID-19, the total population $N(t)$ is divided into susceptible individuals $S(t)$, exposed individuals $E(t)$, infected individuals $I(t)$, confirmed individuals $Q(t)$, and removed individuals $R(t)$. We make the following assumptions:

(1) The exposed individuals $E(t)$ have the ability to infect susceptible individuals S(t).
(2) The removed individuals $R(t)$ have immunity during the epidemic.
(3) Individuals' birth and death rates are ignored.

In order to describe the spread of COVID-19, we establish a corresponding dynamical model based on the policies of epidemic control in Guangdong and Hunan Provinces. The following takes Guangdong Province as an example of mathematical analysis. We study the dynamic modeling in three stages. The first stage: the first confirmed case appeared until the Spring Festival (1.19–1.24). Each province has hospitals that treat and isolate cases. In order to prevent large-scale infection, the confirmed cases $Q(t)$ were treated in the province, indicating that they did not migrate. **Figure 3** demonstrates the transmission of COVID-19 and population migration in detail. Based on the above assumptions, we establish the COVID-19 transmission dynamical modeling **Eq. (1)**:

$$\begin{cases} \frac{dS(t)}{dt} = -\frac{\beta_1 SE + \beta_2 SI}{N} + (a-b)S, \\ \frac{dE(t)}{dt} = \frac{\beta_1 SE + \beta_2 SI}{N} - \delta E + (a-b)E, \\ \frac{dI(t)}{dt} = \delta E - mI + (a-b)I, \\ \frac{dQ(t)}{dt} = mI - \gamma Q, \\ \frac{dR(t)}{dt} = \gamma Q. \end{cases} \quad (1)$$

Here, δ denotes the transfer rate of exposed individuals to infected individuals, so the incubation period is $1/\delta$. The recovery rate of confirmed individuals is γ. The parameter m is the confirmation rate of infected individuals. Susceptible individuals are infected with COVID-19 through contact with exposed individuals and infected individuals. In particular, the novel coronavirus incubation period is infectious, so the parameters β_1 and β_2 are the transmission incidence rates from exposed individuals and infected individuals to susceptible individuals, respectively; a and b denote the immigration rate and emigration rate, respectively.

The second stage: during the Spring Festival (1.24–1.30), the Guangdong Provincial Government has increased control efforts to investigate suspected cases. In addition, people's awareness of the epidemic has gradually increased. We assume that the population has not moved across provinces during this period. The dynamical modeling (2) is as follows:

$$\begin{cases} \frac{dS(t)}{dt} = -\frac{\beta_1 SE + \beta_2 SI}{N}, \\ \frac{dE(t)}{dt} = \frac{\beta_1 SE + \beta_2 SI}{N} - \delta E, \\ \frac{dI(t)}{dt} = \delta E - mI, \\ \frac{dQ(t)}{dt} = mI - \gamma Q, \\ \frac{dR(t)}{dt} = \gamma Q. \end{cases} \quad (2)$$

The third stage: due to the nationwide resumption of work, the population began to move across the provinces. At this stage, the prevention and control measures were quite perfect, and the relevant departments immediately quarantine infected individuals and monitor the people who are in close contact with them. The dynamical modeling **Eq. (3)** is as follows:

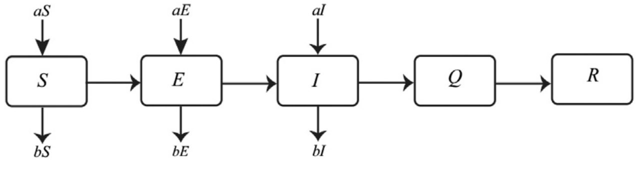

FIGURE 3 | Before the Spring Festival, the flowcharts of COVID-19 infectious disease model. $S(t)$, $E(t)$, $I(t)$, $Q(t)$, and $R(t)$ represent susceptible, exposed, infected, confirmed, and removed populations.

$$\begin{cases} \frac{dS(t)}{dt} = -\frac{\beta_1 SE}{N} + (a-b)S, \\ \frac{dE(t)}{dt} = \frac{\beta_1 SE}{N} - \delta E, \\ \frac{dI(t)}{dt} = \delta E - mI, \\ \frac{dQ(t)}{dt} = mI - \gamma Q, \\ \frac{dR(t)}{dt} = \gamma Q. \end{cases} \quad (3)$$

Before and after the Spring Festival, Guangdong Province was opposite to the overall population mobility of Hunan Province. In the modeling, parameters a and b are used to describe the migration situation of the two provinces (shown in **Table 1**).

Since the modeling in the three stages is roughly the same, we only conduct mathematical analysis on the first stage. Below, we calculate the basic reproduction number R_0 by using the method of the next-generation matrix [38]. Denote

$$\mathcal{F} = \begin{pmatrix} \frac{\beta_1 SE + \beta_2 SI}{N} \\ 0 \\ 0 \end{pmatrix}, \quad \nu = \begin{pmatrix} \delta E - (a-b)E \\ -\delta E + mI - (a-b)I \\ -mI + \gamma Q \end{pmatrix}, \quad (4)$$

By calculating the Jacobian Matrix at the disease-free state E_0, we have

$$F = \begin{pmatrix} \beta_1 & \beta_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad V = \begin{pmatrix} \delta - a + b & 0 & 0 \\ -\delta & m - a + b & 0 \\ 0 & -m & \gamma \end{pmatrix}. \quad (5)$$

Then,

$$FV^{-1} = \begin{pmatrix} \frac{1}{\delta + b - a} & 0 & 0 \\ \frac{\delta}{(\delta + b - a)(m + b - a)} & \frac{1}{m + b - a} & 0 \\ \frac{m\delta}{\gamma(\delta + b - a)(m + b - a)} & \frac{m}{\gamma(m + b - a)} & \frac{1}{\gamma} \end{pmatrix}. \quad (6)$$

So

$$R_0 = \rho(FV^{-1}) = \frac{\beta_1}{\delta + b - a} + \frac{\beta_2 \delta}{(m + b - a)(\delta + b - a)}. \quad (7)$$

If $R_0 > 1$, we can get the endemic equilibrium $E^* = (S^*, E^*, I^*, Q^*, R^*)$.

TABLE 1 | The migration relationship between Guangdong Province and Hunan Province.

Time	The relationship between *a* and *b*	
	Guangdong Province	**Hunan Province**
Before the Spring Festival	$a < b$	$a > b$
During the Spring Festival	$a = b$	$a = b$
After the Spring Festival	$a > b$	$a < b$

$$\begin{cases} S^* = \dfrac{(\delta+\mathrm{b}-\mathrm{a})(\mathrm{m}+\mathrm{b}-\mathrm{a})\mathrm{N}}{(\beta_1(\mathrm{m}+\mathrm{b}-\mathrm{a})+\beta_2\delta)\mathrm{I}^*}, \\ E^* = \dfrac{\mathrm{m}+\mathrm{b}-\mathrm{a}}{\delta}\mathrm{I}^*, \\ I^* = \dfrac{(\mathrm{a}-\mathrm{b})\delta\mathrm{N}}{\beta_1(\mathrm{m}+\mathrm{b}-\mathrm{a})+\beta_2\delta}, \\ Q^* = \dfrac{\mathrm{m}}{\gamma}\mathrm{I}^*, \\ R^* = \mathrm{mI}^*. \end{cases} \quad (8)$$

3. RESULTS

3.1. Parameters Estimation

In our study, the first stage is the early phase of the epidemic when infected individuals and exposed individuals are freely contacted with susceptible people in public places, so $\beta_1 = \beta_2$. In the second stage, during the Spring Festival, the communities investigated the activities of residents. Anyone who came back from Wuhan and had a history of contact with Wuhan personnel should be quarantined at home for 14 days. Therefore, we assume $\beta_2 = \frac{1}{14}\beta_1$. In the third stage, the medical conditions and control measures were perfect; it is assumed that $\beta_2 = 0$. The parameter γ, which depends on the actual infection cases, does not affect the parameters' estimation of the model.

Since the epidemic occurred before the Spring Festival, the initial value of the susceptible population $S(t)$ equals 1.1521×10^8 of the permanent population in Guangdong Province [29]. By the time the hospital detected the first case, many people had already been infected. Based on the data of confirmed cases reported by Guangdong health and Health Commission on the second day, we assume that the initial value of infected individuals $I(t)$ is 10. Since the COVID-19 has an average incubation period of 5 days, we assume that the initial value of exposed individuals $E(t)$ is 110 based on the data from the Health Commission of Guangdong Province about 5 days after the release of the report. According to the characteristics of the COVID-19 incubation period [39], we chose $\delta_1 = \delta_2 = \frac{1}{3.4}$, $\delta_3 = \frac{1}{6.8}$. Before the Spring Festival, the emigration rate is much greater than the immigration rate. According to Baidu migration data [27], we assume that $a = 0.01, b = 0.24$.

Similarly, we assume that the initial value of the susceptible population $S(t)$ equals 6.91838×10^7 of the permanent population in Hunan Province [29]. The initial value of exposed individuals $E(t)$ is 110, and the number of infected individuals $I(t)$ is 21. Moreover, we chose $\delta_1 = \delta_2 = \frac{1}{3.1}$, $\delta_3 = \frac{1}{6}$. Before the Spring Festival, the immigration rate in Hunan Province is much bigger than the emigration rate according to Baidu migration data [27], so $a = 0.12, b = 0.001$.

In this work, we estimate the parameters m and β_1 by the least-squares method. **Figure 4** unveils the time evolution of the cumulative and the daily new confirmed cases in three stages. The parameter values of our simulation are shown in **Table 2**. **Figure 4** indicates that the cumulative value of confirmed cases in Guangdong Province reaches 1356 and COVID-19 will disappear after 40 days. The peak value time of daily new confirmed cases is January 31, which is the same date as reported.

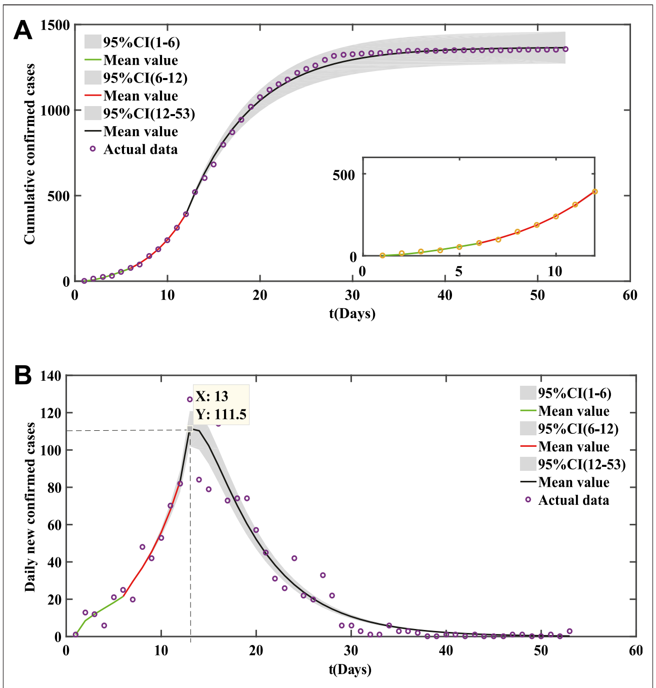

FIGURE 4 | Fitting results of cumulative COVID-19 cases in Guangdong Province. **(A)** Cumulative confirmed cases. **(B)** Daily new confirmed cases. Initial value of parameter: $S(0) = 1.1521 \times 10^8$ [29], $E(0) = 220, I(0) = 10$, $Q(0) = 1, R(0) = 0$.

Figure 5 shows the simulation results of the cumulative and the daily new confirmed cases in Hunan Province. The parameter values of the fitting result are shown in **Table 3**. From January 21 to February 29, the cumulative number of confirmed cases in Hunan Province reached 1018. It can be seen that the daily new confirmed cases in Hunan Province were slower than that in Guangdong Province from the simulation results. Our dynamical model indicates that the epidemic peak in Hunan Province occurred on February 2 and will disappear at the end of February.

3.2. Impact of Population Migration

In order to discuss the impact of population migration around the Spring Festival on the spread of COVID-19, we analyze the parameters a (immigration rate) and b (emigration rate) of Guangdong and Hunan Provinces which have been shown in **Figures 6**, **7**, respectively.

Due to the large number of external population in Guangdong Province, the emigration rate of the population needs to be discussed before the Spring Festival; we find that the greater the emigration rate of the population, the smaller the final scale of the cumulative confirmed cases (shown in **Figure 6A**) and the lower the peak value of daily new confirmed cases (shown in **Figure 6C**).

Through **Figures 6B,D**, we can see the impact of the immigration rate on the confirmed cases of COVID-19 after the Spring Festival when many industries began to resume work. As we can see, if the

TABLE 2 | Parameter estimation of COVID-19 in Guangdong Province.

Parameter	Estimated value			Source
	The first stage	The second stage	The third stage	
β_1	0.3346	0.4648	0.0010	Estimated
β_2	0.3346	0.0332	0	Estimated and calculated
a	0.01	0	0.1	[27]
b	0.24	0	0.005	[27]
δ	$\frac{1}{3.4}$	$\frac{1}{3.4}$	$\frac{1}{6.8}$	[37]
m	0.1836	0.2291	0.3432	Estimated
γ		$\frac{1}{30}$		Estimated
R_0	1.0923	1.6229	0.0068	calculated

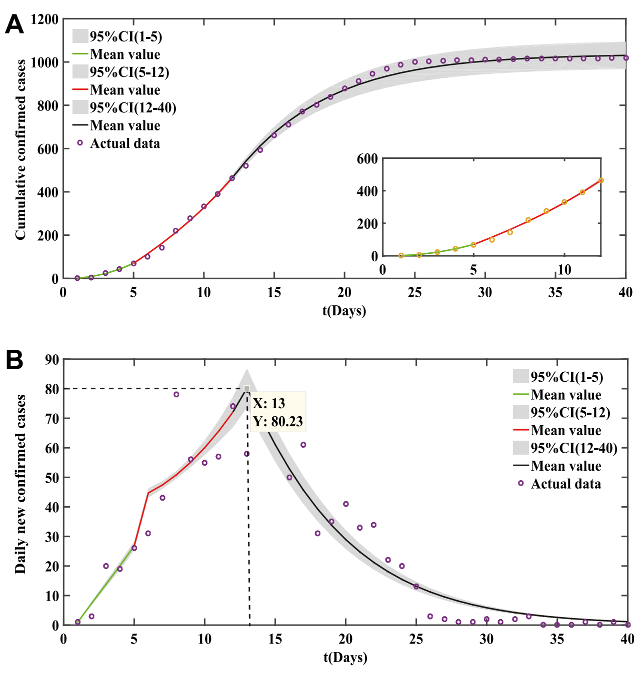

FIGURE 5 | Fitting results of cumulative COVID-19 cases in Hunan Province. **(A)** Cumulative confirmed cases. **(B)** Daily new confirmed cases. Initial value of parameter: $S(0) = 6.91838 \times 10^7$ [29], $E(0) = 110, I(0) = 21, Q(0) = 1, R(0) = 0$.

immigration rate is small, the final scale of confirmed cases will not change, whereas if the immigration rate is too large, the number of confirmed cases will increase with the increase of immigration rate, and the epidemic has a second outbreak. Relevant departments of Guangdong Province should strengthen the restrictions on the number of external population when resuming work.

For the population flow in Guangdong Province, Hu et al. studied the evaluation and prediction of the COVID-19 variations at different input population [40]. Both our research and that by Hu et al. draw the conclusion that there will be a risk of secondary outbreak when the input population flow is so severe that the population movement changes. Taking January 27 to February 20, 2020, as the research period, they established the *SEIRQ* dynamical modeling to simulate and predict the epidemic in Guangdong Province. In their work, imported population $p(t)A(t)$ and exported population $B(t)$ were both constants. Through the four time points of February 6, February 16, February 24, and March 5, 2020, Hu et al. discussed the impact of imported population and quarantine strategies on the epidemic in Guangdong Province, including cumulative and daily new confirmed cases. In this study, our dynamical modeling uses index input and output to represent the actual data immigration rate and emigration rate. In addition, we study the dynamical modeling in three phases around the Spring Festival, which reflects COVID-19 variations.

On the contrary, Hunan Province has a large number of people who work in other provinces, so we discuss the

TABLE 3 | Parameter estimation of COVID-19 in Hunan Province.

Parameter	Estimated value			Source
	The first stage	The second stage	The third stage	
β_1	0.1798	0.3961	0.0022	Estimated
β_2	0.1798	0.0283	0	Estimated and calculated
a	0.12	0	0.01	[27]
b	0.01	0	0.11	[27]
δ	$\frac{1}{3.1}$	$\frac{1}{3.1}$	$\frac{1}{6}$	[37]
m	0.1998	0.2291	0.3308	Estimated
γ		$\frac{1}{30}$		Estimated
R_0	3.8828	1.3265	0.0132	Calculated

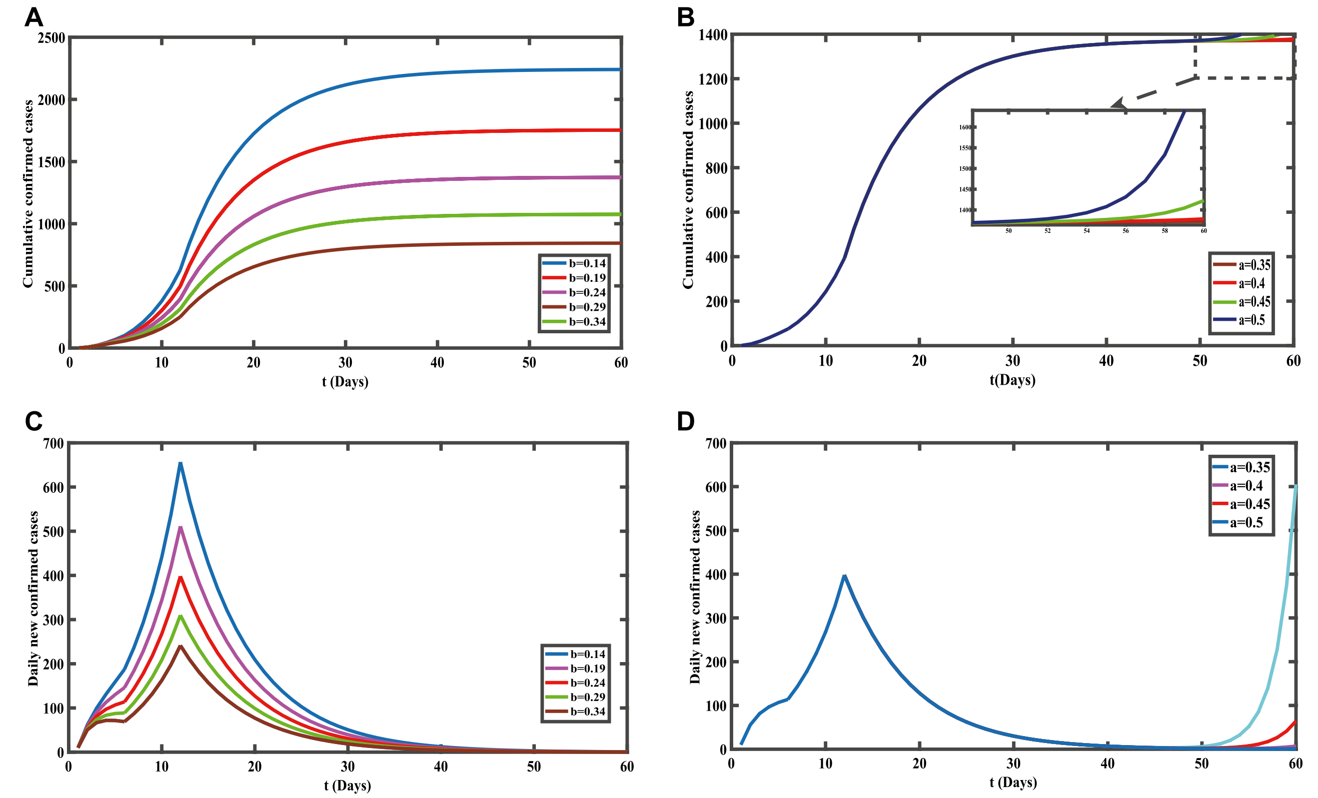

FIGURE 6 | Influence of population migration on COVID-19 cases in Guangdong Province before and after the Spring Festival. **(A)** Cumulative confirmed cases before the Spring Festival. **(B)** Cumulative confirmed cases after the Spring Festival. **(C)** Daily new confirmed cases before the Spring Festival. **(D)** Daily new confirmed cases after the Spring Festival.

immigration rate of the population before the Spring Festival. The greater the immigration rate of the population before the Spring Festival, the larger the final scale of cumulative confirmed cases (shown in **Figure 7A**) and the higher the peak value of the daily new confirmed cases (shown in **Figure 7C**).

After the Spring Festival, people began to resume work, so **Figures 7B,D** show the impact of the immigration rate on the confirmed cases of COVID-19. The relationship between the emigration rate and the confirmed cases is not obvious, and the final scale tends to be stable. This indicates that the scale of the emigrated population in Hunan Province after the Spring Festival has a small impact on the spread of COVID-19, which can be understood as the epidemic has been controlled.

For the transmission of COVID-19 in Hunan Province, Jia et al. established an *eSIR* model (Extended SIR Model) with time-varying transmission rates [41]. According to the model analysis, there are two turning points in the disease. And they predicted that the end of the epidemic of COVID-19 was March 3. They used the Markov chain Monte Carlo (*MCMC*) method to estimate the average basic reproduction number as 3.16 (CI: 1.73–5.25), which is roughly the same as ours. Both our study and that by Jia et al. consider the time factor. Compared with our work which reflects this factor by segmenting the dynamical modeling, Jia et al. reflected it through the transmission rate. In this paper, the turning points of the given model are January 25 and February 1, and the epidemic disappeared after February 29, which is close to the date given in Ref. 39.

4. DISCUSSION

Taking Hunan Province and Guangdong Province as examples, this paper uses dynamical systems to study the impact of population migration on the spread of COVID-19. We establish the *SEIQR* model in three stages and calculate the basic reproduction number for each stage. Subsequently, the actual data released by the Health Commission was used for fitting to prove the rationality of the model. In addition, we discussed in detail the impact of population migration around the Spring Festival on the spread of COVID-19.

Before the Spring Festival, a large-scale population moved out of Guangdong Province, and the number of people infected with COVID-19 is decreasing. After the Spring Festival, the industries began to enter the period of resuming work, and the migrant population began to move in. If the immigrant population is too large, the disease may have a second outbreak. The Guangdong Provincial Government should restrict the entry of the population reasonably. For Hunan Province, most of the migrant workers returned home for the Spring Festival. As the

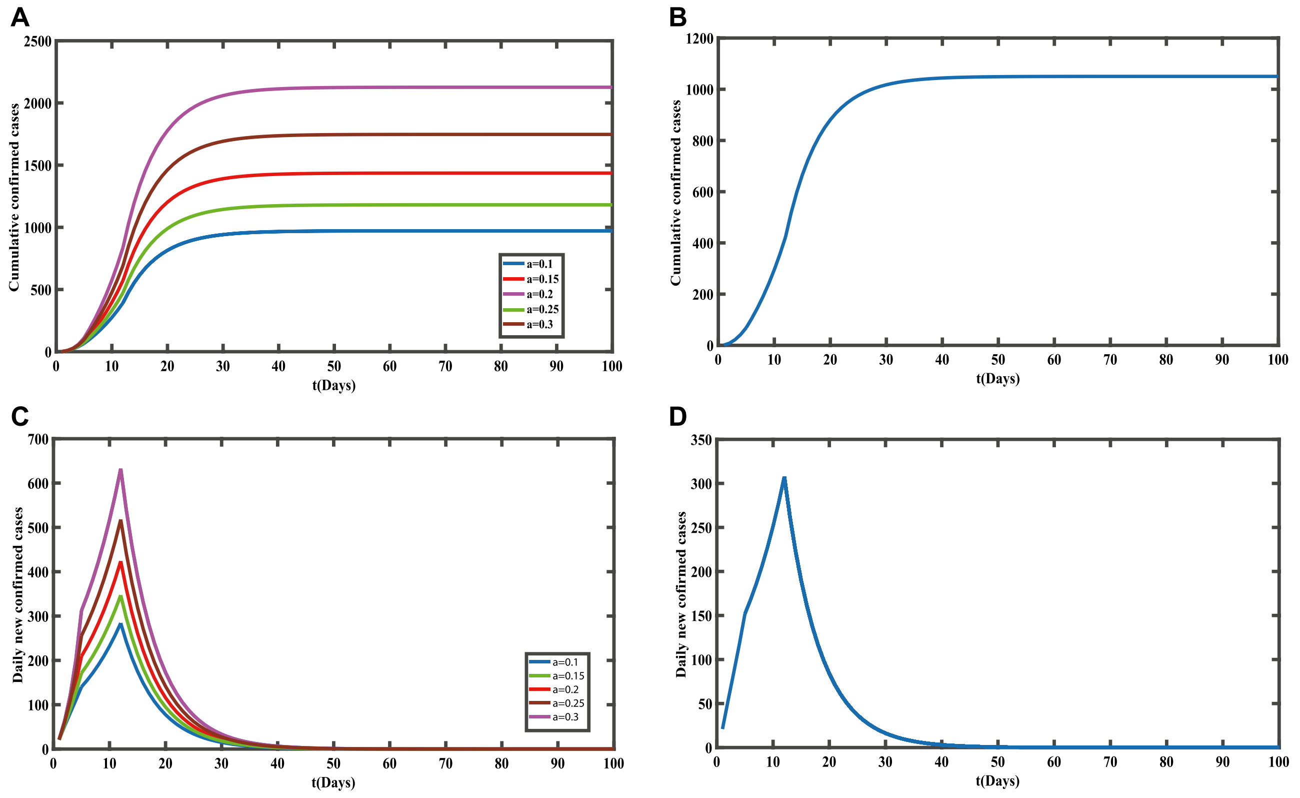

FIGURE 7 | Influence of population migration on COVID-19 cases in Hunan Province before and after the Spring Festival. **(A)** Cumulative confirmed cases before the Spring Festival. **(B)** Cumulative confirmed cases after the Spring Festival. **(C)** Daily new confirmed cases before the Spring Festival. **(D)** Daily new confirmed cases after the Spring Festival.

Spring Festival approached, the population began to immigrate in large numbers, and the number of people infected with COVID-19 continued to rise. After the Spring Festival, population emigration has little effect on the spread of COVID-19 in Hunan Province. The larger population in Guangdong Province may be the reason why the final scale of the cumulative confirmed cases in Guangdong Province is larger than that in Hunan Province. Before the Spring Festival, a large number of people immigrated to Hunan Province, which led to a large increase in the daily new confirmed cases, indicating that the population migration before the Spring Festival accelerated the spread of COVID-19. During the Spring Festival, the growth rate of daily new confirmed cases in Guangdong Province slowed down. At the beginning of February, the daily new confirmed cases in both provinces reached a peak. Subsequently, the number of daily new confirmed cases began to decline and cleared after 40 days. That is to say, the prevention and control measures made by the country in the early stage have well controlled the development of the epidemic, and the risk of people resuming work was reduced.

This work still has many shortcomings and needs to be further improved: 1) in the early stage of the spread of COVID-19, we do not consider asymptomatic infections when establishing the *SEIQR* modeling; 2) this paper studies the early stage of the epidemic when the confirmed cases may have errors because of the limited detection and medical level. The data of population migration is based on the positioning of software and the analysis of big data, which may lead to population deviation; 3) our work does not take spatial factors into consideration, nor does it study the characteristics of spatial diffusion based on the reaction-diffusion equation [42, 43]. This article analyzes the impact of population migration on the spread of COVID-19 from the perspective of dynamical modeling. Although there are some limitations, it has a certain guiding significance to control the local epidemic due to population movements.

DATA AVAILABILITY STATEMENT

All datasets presented in this study are included in the article/Supplementary Material.

AUTHOR CONTRIBUTIONS

All authors have made great contributions to the writing of study and approved the submitted version. XG, LM, and SG established dynamical modeling. LM participated in the program design and provided valuable comments on the manuscript writing. LL collected and processed the relevant published data. SG and LL guided and revised the manuscript.

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