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An interplay model for rumour spreading and emergency development

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ABSTRACT

Rumours influence how people make decisions in an emergency-affected environment. Conversely, the development of situation is affected by public action as well. We present a model for describing the interplay between rumour spreading and emergency development. Then, we describe a formulation of this model and derive, from differential equations for some possibility of the positive role of rumours in the control of situation and social loss. Our results show that rumour spreading at certain rate has positive effects on situation stability and especially has delaying effects on the rapid proliferation of an emergency. Finally, we outline a strategy for authorities that can contribute to rumour management in an emergency event.

1. Introduction

Rumour is an important form of social communication, and its spreading plays a significant role in a variety of human affairs. They may contain confidential information about public figures, or news concerning important social or economic issues. Rumour can shape the public opinion of a society or a market by affecting the individual beliefs of its members.

Hayakawa [1] defines rumour as a kind of social phenomenon that a similar remark spreads on a large scale in a short time through chains of communication. According to this definition, first it makes clear the differences between rumour and other phenomena that could be confused as rumour and sometimes difficult to be distinguished from it. For instance, gossip targets a precise person and essentially only propagates within its friendship connections [2]. Secondly, we can understand the phenomena without thinking over the questions such as how a rumour occurs, whether it tells the truth, and what inspires people to spread it. These questions have been well discussed in the literature. For instance, Shibutani [3] regards rumour as "collective problem-solving", in which people "caught" in ambiguous situations try to "construe a meaningful interpretation . . . by pooling their intellectual resources." In this paper, rumour is viewed as an unverified account or explanation of events circulating in informal channels and pertaining to an emergency event in public concern, and can contain some degree of both falseness and truth. When the public are in great need for information to fill the gap between their anxiety and the lack of information from normal media channels, they are likely to be susceptive to any information, hence the rumour is accepted to serve this purpose.

Prior research has documented a relationship between disaster-related rumours and panic among civilians since World War II. As problematic rumours often cause public confusion, chaos and panic when emergency events occur [4], those studies have mainly focused on their negative effects in various aspects [5,6]. The issue whether rumours have a positive import on the development of an emergency event has been overlooked. Rumours are uncertain information spreading via word-of-mouth or other complex patterns. Indeed, false and exaggerated rumours such as those in the SARS Crisis did bring

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seriously negative effects to society, whereas we emphasize that rumours can also benefit the development of an emergency in some cases. For example, the public's response to an emergency could objectively promote its settlement.

Although mathematical models for the spread of rumours have been introduced in some fields such as financial markets [7,8] and social networks [9], rumours generated in emergencies, in some sense, were thought to be something irrational and were rarely modelled. The aim of this paper is to propose a mathematical framework for studying the effects of rumour spreading in emergencies, especially its positive effects on emergency development. The results are expected to provide another perspective of coping with the rumours in emergency management.

2. Related works

2.1. Development of emergencies

An emergency is an exceptional event that exceeds the capacity of normal resources and organisation to cope with it [10] and a situation which poses an immediate risk to health, life, property or environment, for example, the Chernobyl nuclear accident, the SARS Crisis, the Indian Ocean tsunami, Hurricane Katrina, the Wenchuan Earthquake, and so on. Most emergencies require urgent intervention to prevent a worsening of the situation, such as the expanding in the region scope, or an increase of the destruction and the loss, or the intensifying of social unrest. The route of the development of emergent events is extremely complex. One strong initial event may trigger an emergency, which develops in a cascade-like manner and finally has a serious impact on human society [11].

Since World War II, an extensive literature has established a variety of developmental models for disasters [12,13], and those studies are oriented to the sequence that begins with a warning of danger and moves through the onset of danger to the problems of alarm, panic, and rescue. Wybo and Latiers [14] focused on the dynamics of human collective activities during emergency periods and on their relations with the occurrence of crises. For organisations, Wybo [15] stated that an emergency situation turns into a crisis when the organisation is overwhelmed and cannot follow the plans. Quarantelli [16] explored the relationship between organisational behavior in disasters and its implications for disaster planning. Although the literature investigated the sequence of events associated with an emergency or human behaviour in extreme situations, none of the models presented are of much help if the goal of emergency research is to detect the spreading rumours' impact on the development of situations.

2.2. The effects of rumours on emergencies

The effects of rumours have been widely documented in many fields such as in markets, social organisations, and disasters. Numerous studies have looked at the negative impact of rumours on the society when emergency events happened. Yang [17] argued that information would be distorted and magnified in the dissemination process for instinct motive for the protection of life and property. Through the "stakeholders" filter, the information that was received, believed and passed by individuals would gradually converge to enhance the "safety of life and property", which would result in a security sense reduction and threat sense accretion. Danzig et al. [6] investigated the human interaction under conditions of stress when unexpected floods struck Port Jervis. Rumours that an upstream dam had burst swept through the city stimulated serious panic and an exodus from the area. Lv and Wang [18] stated that the spread of rumours, the public panic and the destruction of social order would interact with one another and could promote a proliferation of a significant emergency event.

In fact, rumours in emergency events also have positive effects. Rumours may cause the public that contact the rumours in the early period to be aware of the latent social risks in advance, and induced them to struggle for obtaining "the right to know" [19]. Yan and Xu [20] investigated the rumour phenomenon in the SARS epidemic in Guangzhou during March 8-9, 2003, and found the core of those rumours was true and they actually conveyed important information to public, whereas most of their surface details were false. They also revealed that rumours play a role of "anti-power" and compel the "authoritative" official channel to make open responses. Molka-Danielsen and Beke [21] suggested in disaster events it could happen that known channels of communication do not exist or are not functional. Rumours can be used to share best-known information when it is unclear who is responsible for the integrity of information and the spreading of factual information. Where organisation and structure does not exist, the rumour may be the mechanism for coping with an event. However, they only present a qualitative model and analysis of the function of rumours in disaster management.

2.3. Mathematical model of rumours

A classical model for the spread of rumour was introduced by Daley and Kendal [22,23]. The Daley–Kendal model and its variants have been used extensively in the past for quantitative studies of rumour spreading [24–26]. Daley and Kendal suggested that rumour spreading has a similarity to the epidemic model.

In the Daley–Kendal model, a closed homogeneously mixing population is classified into three mutually groups which are respectively called ignorants, spreaders and stiflers. The rumour is spread by pair-wise contacts between spreaders and others in the population. Any spreader involved in a pair-wise contact can infect the other individual with the rumour. If

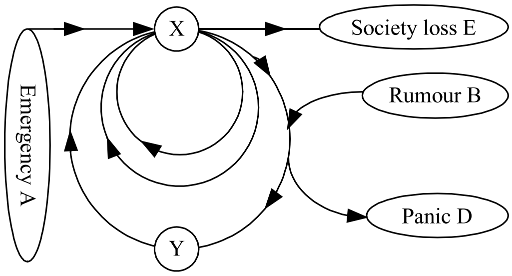

Fig. 1. Relationship between emergency development, rumour spreading and social loss.

this other individual is an ignorant, it becomes a spreader. In the other two cases, either one or both of those involved in the contact learn that the rumour is "known" and decide not to transmit the rumour, thereby becoming stiflers [22].

A number of studies proposed more complex models of rumour spreading along large social networks, in particular those which are mediated by the Internet, such as "virtual" communities and email networks. Zanette performed simulations of the deterministic Maki–Thompson [24] model on both static [27] and dynamic [28] small-world networks. Moreno et al. [29] studied the stochastic version of the Maki–Thompson model on scale-free networks and numerical solution of a set of mean-field equations. Nekovee et al. [30] proposed a model of rumour spreading on complex networks and described a formulation of this model on networks in terms of Interacting Markov Chains.

Although above models may adequately describe rumour spreading in everyday life, via individual word-of-mouth or complex interaction networks, they become highly inadequate when applied to a description of the relationship between an emergent event and rumours. Such events, including natural disasters, public health emergencies and terrorist incidents, typically produce rumours in a very short time, and simultaneously these situations could be influenced by those rumours.

In this paper, we make several contributions to the study of rumour dynamics when an emergency event happens. First, we introduce a new model of rumour spreading in emergencies which provides a realistic description of this process. In a macroscopic view, our model discusses the interplay between the spreading rate of rumours and the emergency development. Second, we describe a formulation of this model and derive, from differential equations for the dynamics of rumour spreading and emergency development. Finally, our model shows that, in some case the rumours can positively influence the development of an emergency.

3. An interplay model for rumour spreading and emergency development

The spread of rumours is a complex socio-psychological process. An adequate modelling of this process requires a correct description of the emergency development in the dissemination process. The model described below is an attempt to formalise and simplify these mechanisms in terms of a set of assumptions.

3.1. Symbols and assumptions

When an emergency event occurs, it inevitably causes some rumours, public panic and social loss. Many studies [17,18, 31] indicate that rumour spreading and emergency development can interact with each other. Fig. 1 shows the proposed interplay model for expressing the relationship between them.

We assume that the development of an emergency is a continuous process and the social loss grows until the situation is brought under control. A is the initial state of an emergency and X is its development state, B is the rumour amount generated in the emergency which is spread at a rate Y. D and E are respectively the caused public panic and social loss.

Suppose that the emergency state X and the spreading rate of rumours Y are continuous functions of time. k_1 denotes the influence degree of the initial state A on state X, and k_1A denotes the magnification in the transitions from A to X. Rumours emerge in X state. k_2 denotes the interplay of the spread of rumours and the state of emergency development. k_3 denotes the combined influence of the current state and rumours on the emergency state. We consider that the rumour spreading has both positive [19–21] and negative effects [17,18] on emergency development, which are respectively denoted by $-k_2BX$ and k_3X^2Y in $\mathrm{d}X/\mathrm{d}t$ equation. Based on the analyses of [17,18], we denote with X^2 the accelerated deterioration of situation under the negative influence of rumour spreading. As an emergency event usually leads to sequential social loss at every stage, $-k_4X$ is used to indicate the degree of society loss caused by the current state and "the part of situation" that would no longer develop into the next stage. In $\mathrm{d}Y/\mathrm{d}t$ equation, k_2BX denotes the rate of rumour spreading proportionate to the rumour amount B and the emergent state. With the development of a situation, the rumours can be gradually verified, hence, we use X^2 to indicate that rumours are reduced by the accelerated situation development in $-k_3X^2Y$, and the reduction is also proportionate to the current rate Y.

Then we can express our model in Eq. (1):

$$\begin{cases} \mathrm{d}X/\mathrm{d}t = k_1A - (k_2B + k_4)X + k_3X^2Y \\ \mathrm{d}Y/\mathrm{d}t = k_2BX - k_3X^2Y. \end{cases} \tag{1}$$

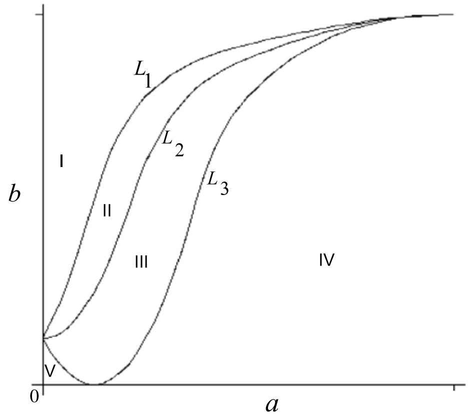

Fig. 2. The first quadrant is divided into five regions by curves L_1, L_2, L_3.

Let $\{x = \sqrt{k_3/k_4}X \quad y = \sqrt{k_3/k_4}Y \quad \tau = k_4 t \quad a = k_1\sqrt{k_3/k_4}A/k_4 \quad b = k_2 B/k_4\}$, then Eq. (1) can be simplified as:

$$\begin{cases} \mathrm{d}x/\mathrm{d}\tau = a - (b+1)x + x^2 y \\ \mathrm{d}y/\mathrm{d}\tau = bx - x^2 y. \end{cases} \tag{2}$$

Where a and b are both positive constant.

3.2. Findings

3.2.1. Rumour spreading at certain rate has a positive impact on the situation control

Let the initial state of emergency A and rumours B in this model be constant. When emergency A occurs, we explore the impact of rumour spreading rate Y on the emergency development X, by looking for the steady state solution of Eq. (1).

According to the singularity theory [32], Eq. (2) only has one singularity point, and Eq. (2) can be translated into Eq. (3) when the coordinate origin is shifted to the singularity point:

$$\begin{cases} \mathrm{d}x/\mathrm{d}\tau = (b-1)x + a^2 y + bx^2/a + 2axy + x^2 y \\ \mathrm{d}y/\mathrm{d}\tau = -bx - a^2 y - bx^2/a - 2axy - x^2 y. \end{cases} \tag{3}$$

The characteristic equation of the linearisation system of Eq. (3) is:

$$\lambda^2 + (a^2 + 1 - b)\lambda + a^2 = 0. \tag{4}$$

According to the roots of characteristic Eq. (4), we divide the first quadrant of the plane aob into five regions (Fig. 2) by the following curves:

$$\begin{cases} L_1 : b = a^2 + 2a + 1 \\ L_2 : b = a^2 + 1 \\ L_3 : b = a^2 - 2a + 1. \end{cases} \tag{5}$$

Due to $b > (a+1)^2$ in region I, $P(a, b/a)$ is an unstable point of Eq. (2); due to $a^2+1 < b < (a+1)^2$ in region II, $P(a, b/a)$ is an unstable focus; due to $(a-1)^2 < b < a^2+1$ in region III, $P(a, b/a)$ is a stable focus; due to $b < (a-1)^2$ in region IV and V, $P(a, b/a)$ is a stable point. When on L_1, i.e., $b = (a+1)^2$, $P(a, b/a)$ is an unstable critical point or a degenerate unstable point. When on L_3, i.e., $b = (a-1)^2$, $P(a, b/a)$ is a stable critical point or a degenerate stable point. When on L_2, i.e., (a, b), the coordinate origin of the linearisation system of Eq. (3) is center, so $P(a, b/a)$ deserves further consideration.

When $b = a^2 + 1$, let $x = (u - av)/(a^2+1)$, $y = v/a$, $\tau = s/a$, Eq. (3) can be translated into (6).

$$\begin{cases} \mathrm{d}u/\mathrm{d}s = v - (u^2 - a^2v^2)/(a^2 b) + (u^2 v - 2auv^2 + a^2)/(a^2b^2) \\ \mathrm{d}v/\mathrm{d}s = -u - (u^2 - a^2v^2)/(ab) - (u^2v - 2auv^2 + a^2v^3)/(ab^2). \end{cases} \tag{6}$$

Then we select functions with formal series [32]:

$$F(u,v) = u^2 + v^2 - \frac{(2+2a^4-3a^2)v^4}{2a^2b^2} + \frac{2u^2v}{ab^2} - \frac{2auv^2}{b} + \frac{(2+a^4-13a^2)u^3v}{4a^3b^2} - \frac{(2+2a^4+a^2)u^4}{2a^4b^2} - \frac{2(a^2-2)v^3}{3a^2b} + \frac{(7a^4-19a^2-2)uv^3}{4a^3b^2} - \frac{2(2a^2-1)u^3}{3ab}. \tag{7}$$

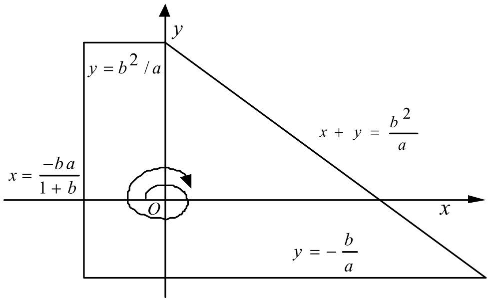

Fig. 3. The borderline of trajectory region.

Based on the trajectory of Eq. (6), we obtain:

$$\frac{\mathrm{d}F(u,v)}{\mathrm{d}s}|_{(5)} = \frac{(a^4+3a^2+a)(u^2+v^2)^2}{4a^3b^2} + o((u^2+v^2)^2). \tag{8}$$

Thus, the coordinate origin of Eq. (6) is a stable focus, namely, the singular point of Eq. (2) is stable.

We have obtained the steady state $(X^*, Y^*) = (a, b/a)(\mathrm{d}X/\mathrm{d}t = \mathrm{d}Y/\mathrm{d}t = 0)$, which shows that rumours have a positive impact on the stability of an emergency when spreading at certain rate, but higher or lower rates are not favourable for the situation control.

Slow rumours may indicate that the public think the situation is not serious enough, which could lead to a further development of an emergency before people are aware of its gravity. On the other hand, if rumours quickly flourish, inevitably they might create a collectively anxious and bewildered atmosphere before effective measures are taken, thereby leading to a proliferation of the emergency event.

3.2.2. Rumour spreading has delaying effects on rapid proliferation of an emergency

As proved above, when the spreading rate exceeds the critical scope (suppose all other values are unchanged), the interplay system between emergency development and rumour spreading cannot reach a stable state (X^*, Y^*). Then, we next prove that, although the system will deviate (X^*, Y^*), it will still be limited to a certain scope, and rumour spreading would draw the system close to the steady state when the situation continues to develop rapidly. In other words, rumour spreading has delaying effects on emergency evolvement.

According to Eq. (3) which is a result of the Eq. (2)'s parallel movement, we obtain:

If $x = -ba/(1+b),\ y \geq -a/b$

$$\mathrm{d}x/\mathrm{d}\tau = a^2b(y+b/a)/(1+b)^2 \geq 0. \tag{9}$$

If $y = -b/a, x \geq -a$

$$\mathrm{d}y/\mathrm{d}\tau = b(a+x) \geq 0. \tag{10}$$

If $y = b^2/a, x \geq -ab/(1+b)$

$$\mathrm{d}y/\mathrm{d}\tau = -b(x+a)(1+b)[x+ab/(1+b)]/a \leq 0. \tag{11}$$

If $x+y = b^2/a, x \geq 0$, Based on Eq. (3)'s trajectory:

$$\mathrm{d}(x+y)/\mathrm{d}\tau|_{(6)} = -x \leq 0. \tag{12}$$

From Eq. (3) to Eq. (12), we know that Eq. (3)'s trajectory will be always a quadrilateral region (see Fig. 3) which is divided by four curves ($x = -ba/(1+b), y = -b/a, y = b^2/a$ and $x+y = b^2/a$). If $b \geq 1+a^2$, Eq. (3)'s singularity point $o(0,0)$ is an unstable focus or point. Thus, Eq. (3) has at least one limit cycle based on the annular-region theorem [32].

If $b > 1+a^2$, let $v = -(x+y), s = (x+a)^2t$, and Eq. (3) can be transformed into

$$\begin{cases} \mathrm{d}v/\mathrm{d}s = x/(x+a)^2 \\ \mathrm{d}x/\mathrm{d}t = -v - [x^3 - (b-2a^2)x^2/a + (1+a^2-b)x]/(x+a)^2. \end{cases} \tag{13}$$

We only need to prove that the limit cycle is one and only due to Eq. (3)'s trajectory which can exist but in the region ($x > -a$ and $y > -b/a$). Let

$$h(x) = x/(x+a)^2 \tag{14}$$

$$H(x) = \int_0^x g(x)\mathrm{d}x \tag{15}$$

$$F(x) = [x^3 - (b-2a^2)x^2/a + (1+a^2-b)x]/(x+a)^2 \tag{16}$$

$$f(x) = F'(x) = [x^3 + 3ax^2 + (3a^2-b-1)x + a(1+a^2-b)]/(x+a)^3. \tag{17}$$

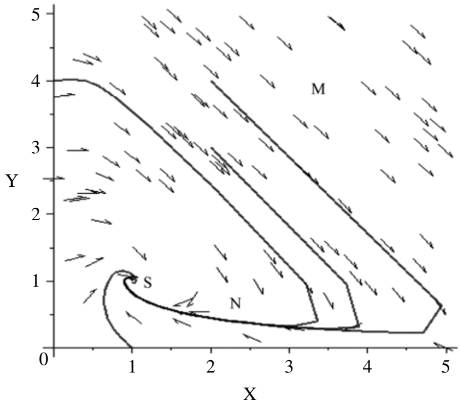

Fig. 4. Partial trajectory when $b < 1 + a^2$.

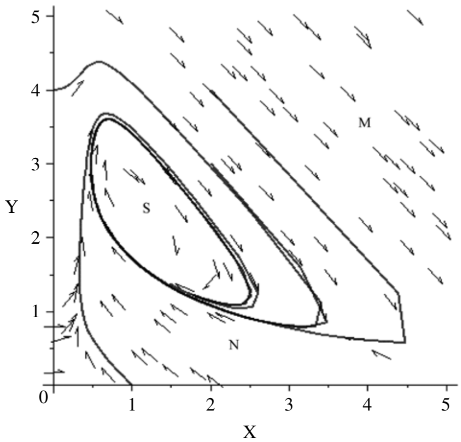

Fig. 5. Partial trajectory when $b > 1 + a^2$.

Then we obtain:

$$f(0) = F'(x) = (1 + a^2 - b)/a^2 < 0 \tag{18}$$

$$xh(x) > 0, \quad x > -a, x \neq 0 \tag{19}$$

$$\lim_{x \to -a} H(x) = +\infty, \qquad \lim_{x \to +\infty} H(x) = +\infty \tag{20}$$

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}x}\left(\dfrac{f(x)}{h(x)}\right) = 1 + \dfrac{2}{(x+a)^2} + \dfrac{b - 1 - a^2}{x^2} > 0 \\ x > -a, \quad x \neq 0. \end{cases} \tag{21}$$

In terms of existence and uniqueness of limit cycle, Eq. (13) exists during at best one limit cycle when $b > 1 + a^2$, and Eq. (3) exists during one and only limit cycle when $b > 1 + a^2$. Then partial trajectory of Eq. (2) is as Figs. 4 and 5 when $b < 1 + a^2$ and $b > 1 + a^2$.

Figs. 4 and 5 illustrate the relationship between the state X of an emergency and spread rate Y of rumours. The focus S of the limit cycle is a steady point. When the situation deteriorates sharply and the spread of rumours is slow, e.g. N, we can see that an appropriate increase of spreading rate will draw N to the stable state S, namely, rumour spreading has delaying effects on the rapid evolution of an emergency (see Fig. 4). However, when the system is at M, the increased rumours will make the track away from the stable state, and especially will speed the development of situation when $b > 1 + a^2$ (see Fig. 5).

In summary, when an emergency occurs, an appropriate spread of rumours would be helpful for the stability of situation and the control of social loss, especially when the situation is developing rapidly. However, too fast-spreading rumours should be prevented or reduced to avoid the possibility that situation becomes out of control. For example, the fast spread of rumours in China's SARS Crisis brought seriously negative effects to society.

In SARS Crisis, the majority of the people via rumours knew for the first time a kind of cryptogenic infectious disease was spreading in Guangzhou [20], and the rumours sounded a warning note to the public [21] and induced part of the population to take some measures for self-protection, such as wearing a respirator. Objectively, those people were safe from the epidemic in this way before the truth was ascertained, which is important for the prevention of further spread of SARS. However, soon afterwards rumours became a pandemic in China because of the slow reaction of the authorities. The public, including those people who had taken the right measures according to rumours, lost their judgment, and at that time the mass media had lost the best opportunities to verify false rumours. Finally, a lot of irrational activities such as panic buying occurred in many areas of China, and the SARS Crisis was aggravated.

The authorities may allow rumours to spread at the early stage of an emergency event and such rumours objectively prompt the public to stay alert to the potential dangers. The authorities should not rashly verify the rumours when they are not able to obtain the real information of the event, as it could cause the public that have taken some action to relax their vigilance. Our study also indicates that the fast spread of rumours goes against the stability of the emergent situation, as it could cause the public to move away from appropriate self-protection and join the panic crowd, or even adopt some irrational measures which could result in unnecessary social loss. What is more serious is that, as in SARS Crisis, the public would no longer believe reports from official channels, prompted by a spate of scares. Therefore, the authorities should respond rapidly to fast spread of rumours in large areas and take steps to manage them, in order to avoid a deteriorating situation caused by rumours.

4. Conclusions

It is not surprising that rumours are rife in an emergency, which is marked by periods of uncertainty and anxiety about the possible damage to individuals. Intuitively, rumours are often seen as negative for the development of a situation, while this paper explores some possibilities for the positive effects of rumour spreading on the control of emergencies, by proposing an interplay model for rumour spreading and emergency development.

Unlike the previous rumour models, our model generally discusses the interplay between the spreading rate of rumours and the development state of an emergency. The results show that rumour spreading at a certain rate has a positive impact on the control of an emergency, and the spread of rumours has delaying effects on it when the situation develops rapidly. The findings of this study have several practical implications for dealing with rumours in emergency management. Key implications are summarised as follows:

1. Rumour spreading at certain rate has a positive impact on the situation control. In particularly, when the facts regarding the emergent situation are unknown in the incipient stage, rumours may serve for a channel of information share and help for coping with unexpected disasters.
2. Desirability of the rumour spreading can increase or decrease in the different developing stages of an emergency. When the emergency event develop rapidly in incipient stage or the truth is not clear, the authorities may allow rumour spreading to evoke the public's reaction to latent dangers and take some appropriate emergency measures. When the rate of rumour spreading is too fast or the obviously false rumours emerge in large amounts, the authorities should take steps to reduce rumour spreading on behalf of situation control.
3. Our model indicates that a slow spread of rumours in the middle and late stages of an emergency can benefit the stability of emergency situation.
4. The authorities should first investigate the circulating rumours and the emergent situation to determine whether the rate of rumour spreading has come to a point threatening the control of an emergency, and then take appropriate strategies to make rumours in favour of emergency management.

In summary, our study contributes to rumour management in an emergent event by offering an interplay model between rumour spreading and emergency development and explaining the different functions of rumour spreading at different stages of emergency development. Because of the possible positive or potentially threatening effects of rumours, it is essential for the authorities to understand the current situation and duly take measures to manage rumours. Authorities with this knowledge will be better able to deal with emergencies, reduce social loss and avoid a public panic.

Acknowledgments

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