



# One cause of pulse-like anomalies observed at Guza before the Wenchuan earthquake

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## Abstract

Many precursor-like anomaly observations prior to the Wenchuan earthquake were reported and analyzed, especially the abnormal strain pulses observed at the Guza station, but there are few discussions of the causes. Stick–slip motion is the basis for description of a great variety of phenomena characterized by the presence of sliding friction. In this article, perturbed Sine–Gordon (SG) equation is established from Bykov’s unsteady-state slip model. Stable solitary solutions of displacement and strain dimension are obtained and nonlinear pulse propagation is simulated using finite-difference modeling, while numerical stability is obtained by the flux-corrected transport method. Considering the solution of SG equation as initial source, a comparison between the modeling results and actual data at the Guza station gives one possible interpretation for this anomaly. During the seismogenic process of the Wenchuan earthquake, faults may likely occur as stick–slip tectonic movements which might be described by SG equation and would generate solitary wave signal. This kind of pulse experiences a forward tilting distortion due to nonlinear effect of the Earth and is received by the borehole strainmeter. Two kinds of nonlinear effects could lead to these special pulses. One is the nonlinear effects in the wave propagation process, and the other is effects of friction and stress in the process of unsteady-state slip. Because of the convergence effect of pulse, the wave would be collapsed at a certain time due to an excessive increase in the tilt angle. Hence, this kind of pulse cannot propagate for a long distance.

**Keyword** Sine–Gordon equation · Numerical modeling · Earthquake dynamics · Nonlinear wave propagation

## Introduction

It has been asserted that earthquakes cannot be predicted (Geller et al. 1997). According to Geller et al. (1997), faulting, as a nonlinear process, is highly sensitive to fine details of physical conditions throughout a large volume, not just in the immediate vicinity of the fault. Since this may be true to some extent for the present, further researches in this field are still needed, especially when a significant number of abnormal pre-earthquake phenomena were reported by numerous publications after the Wenchuan earthquake (Ouyang et al. 2009; Ma and Wu 2012). On

the basis of laboratory data and field observations, certain records of anomalous strains or their induced signals occurring prior to ruptures have been reported in the past (Takemoto 1995; Vallianatos and Tzanis 1998; Vallianatos et al. 2004). Both theoretical studies and experimental results indicated that stress and strain waves might be present in the rocks before the main rupture (Jiang and Yin 2005; Liang et al. 2010). According to available observations, anomalous changes in stress and strain prior to the earthquake occurrence can be very significant at the epicenter and in its vicinity. For example, considerable anomalous changes prior to the occurrence of the 1976 Tangshan earthquake were even recorded with low-precision instruments (Qiu et al. 1988). Anomalous tremors were widely recorded by seismometers, gravimeters, and tiltmeters in the National Digital Seismograph Network of China (NDSN) prior to the 2008 Ms 8.0 Wenchuan earthquake (Hu and Hao 2009; Deng et al. 2012). Based on the study and analysis of the relationship between

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amplitude variations of the seismic signals and the strength and path of typhoons, Hu and Hao (2009) suggested that it is not likely the “pre-earthquake perturbations” of the Wenchuan earthquake solely originated from the typhoon-induced microseisms. The cause and mechanics of the pre-earthquake perturbation are therefore worth further study. On the other hand, Qiu et al. (2011) pointed out that anomalous strain changes have been recorded by borehole strainmeter at the Guza station (located at the southwestern end of the Longmenshan Fault) from time to time since about 1 year before the Wenchuan earthquake. The anomaly was characterized by steps and/or asymmetrical pulses of short periods (minutes–hours) and suggested they might be resulted from the background tectonic movement. Liu et al. (2011) proposed that a larger earthquake would have a stronger perturbation signal after analyzing the pre-earthquake crustal strain anomaly of four major earthquakes, including the Wenchuan earthquake.

However, few of the aforementioned studies on pre-earthquake abnormal strain changes, especially the study by Ma and Wu (2012) that summarized numerous suspected pre-earthquake abnormalities, have provided analysis on the characteristics of the strain wave or physical model.

In 1910, H. F. Reid (1910) suggested the famous Reid’s elastic rebound theory for strong earthquakes, which clearly elaborated the correlation between faulting and shallow earthquakes. The elastic rebound theory was then further improved after the introduction of the stick–slip concept in earthquake research (Brace and Byerlee 1966; Byerlee 1978). Burridge and Knopoff (1967) presented the famous Burridge & Knopoff (BK) model after an investigation of fault friction in earthquake mechanisms through physical experiments and numerical studies. The original BK model was improved by Carlson and Langer (1989) and Carlson (1991) when they obtained a partial differential equation that describes the BK model. Wu and Chen (1998) simplified the relatively complicated partial differential equations into the classical Sine–Gordon (SG) equation and derived a solitary wave solution from the equation. Bykov (2008) suggested that the whole process from the initial slip acceleration at the fault to the end of the slip motion could be described by the generalized SG equation, while the strain waves propagating along the contact surface should occur prior to the slip motion. He further pointed out that the SG equation is suitable for describing a series of observed earthquake data, slow strain waves, corresponding fault mechanics, and the characteristics of subducting plates (Bykov 2014, 2015; Bykov and Trofimenko 2016).

Based on the perturbed SG equation obtained from Bykov’s unsteady-state slip model, this paper derives stable solitary solutions of displacement dimension and

strain dimension and takes them as initial sources. The nonlinear propagation of the solitary wave is modeled using the finite-difference numerical simulation method, and the factors affecting their propagation and evolution are also analyzed. Through a comparison between the simulation results and the actual data at the Guza station, one possible potential physical mechanism for the generation of strain pulses is discussed.

## Model description and its solutions

The contacting surface of blocks is a homogeneous sinusoidal grained surface within asperity. The asperities of the contact surfaces stick to each other (Fig. 1a). The coarse surface (quasi-periodic structure) induces a periodic restoring force which tends to bring the fault back to equilibrium after a local slip (Fig. 1b).

Based on this quasi-periodic surface of blocks, a nonlinear mathematical model of an unsteady-state slip on contact surface was proposed by Bykov (2001, 2015) and was described by the one-dimensional perturbed SG equation,

$$\frac{\partial^2 U}{\partial \xi^2} - \frac{\partial^2 U}{\partial \eta^2} = \sin U + \alpha_0 \left( \frac{\partial U}{\partial \eta} \right)^2 - \sigma(\eta) \quad (1)$$

$$U = 2\pi \frac{u}{a}, \xi = \frac{\pi x}{ap}, \eta = \frac{\pi \omega_0 t}{p}, p^2 = \frac{a^2 D_t}{4mgh}, \omega_0^2 = \frac{D_t}{m},$$

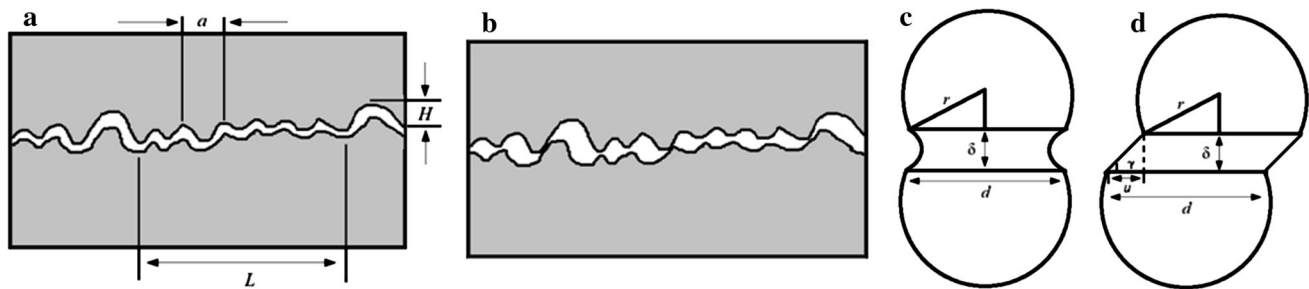
$$\alpha_0 = \frac{9}{8\pi} \frac{a\mu}{d\delta\rho(gh)^{1/2}}$$

where  $u$  is the displacement of blocks along the fault;  $a$  is the distance between block centers;  $D_t$  is the shear stiffness of the junction;  $m$  is the block mass;  $h$  is the distance between the block centers of the adjacent block layers;  $g$  is the acceleration due to gravity;  $\mu$  is the viscosity of gouge;  $d$  is the diameter of the circular junction;  $\delta$  is the fault gouge thickness;  $\rho$  is the density of blocks;  $\alpha_0$  is the friction;  $\sigma(\eta)$  is the function that refers to stress at the junction.

Set  $\sigma \rightarrow \sigma_0$  the elliptical function modulus  $k \rightarrow 1$ , the solution to Eq. (1), in the form of a traveling wave  $U = U(\tau) = U(\xi - \beta\eta)$  (where  $\beta = (n^2 - 1)^{1/2}/n$  is the dimensionless velocity, and  $n > 1$  is the separation constant) is (Bykov 2000)

$$U = \arcsin \sigma_0 + 4 \arctan \left[ \exp \left( \left( \frac{\sigma_0}{2\alpha_0\beta^2} \right)^{1/2} (\tau - \tau_0) \right) \right] \quad (2)$$

Let  $\tau_0 = 0$  be the arbitrary constant; with the parameters of (1), the solution to (2) and its derivative  $\partial u(x, t)/\partial x$  become



**Fig. 1** Surface of blocks with quasi-periodic structure. **a** Structure of the contact, **b** relative movement, **c** and **d** are the diagrams of movement at one asperity (after Bykov 2001)

$$u(x, t) = \frac{a}{2\pi} \arcsin \left[ \frac{2\alpha_0(n^2 - 1)}{(1 + 4\alpha_0^2 n^2(n^2 - 1))^{1/2}} \right] + \frac{2a}{\pi} \arctan \left[ \exp \left( \frac{x - V_\alpha t}{\Delta} \right) \right] \quad (3)$$

$$\frac{\partial u(x, t)}{\partial x} = \frac{a}{\pi \Delta} \operatorname{sech} \left( \frac{x - V_\alpha t}{\Delta} \right) \quad (4)$$

where

$$V_\alpha = a \left( \frac{D_t}{m} \right)^{1/2} \frac{(n^2 - 1)^{1/2}}{n(1 + 4\alpha_0^2 n^2(n^2 - 1))^{1/4}}$$

$$\Delta = \frac{a^2 \omega_0}{2\pi n(gh)^{1/2}}$$

In the absence of friction  $\alpha_0 = 0$ , the solution to (1) coincides with that of the classical SG equation, and the  $V_\alpha$  will be constant as  $V = \frac{a}{2r} \left( \frac{3D_t}{\pi r \rho_s} \right)^{1/2} \frac{(n^2 - 1)}{n}$ . From Eqs. (3) and (4) (in the absence of friction  $\alpha_0 = 0$ ), the waveform diagrams illustrated in Fig. 2 can be obtained. The shape of the displacement solution of SG equation seems to resemble a permanent displacement on the surface of fault, while that of the strain solution is similar to a large pulse.

There are more than 10 parameters in this mathematical model, and many of them are difficult to be measured, such as  $D_t$ ,  $m$ ,  $\sigma$ . So some researchers treated this kind of model as phenomenological. Wu and Chen (1998) provided

approximate or phenomenological description of slip-dependent friction by SG equation. Their results were similar to Eq. (3). Without considering the process of the source movement in detail, period of the solution ( $V_\alpha$  and  $\Delta$ ) is what we need, and we can roughly estimate it from actual data.

## Strain pulses at the Guza station

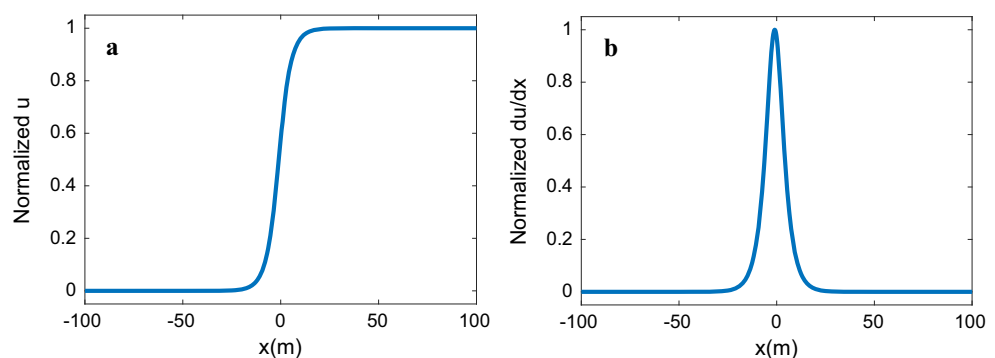
### Original data

The Guza station is located in the southwest extension of the Longmenshan Fault zone. The YRY-4 borehole strainmeter was installed in October 2006, at a depth of 40 m (Qiu et al. 2011). The recordings have been kept continuously with the sampling of one per minute. Anomalous strain changes have been recorded by the Guza station since about one year prior to the Wenchuan earthquake. The anomalies were characterized by short period (minutes–hours) pulse-like shapes. In order to evaluate the observations, an index of data credibility is established based on the self-consistency equation (Qiu et al. 2013).

$$C_{95} = 1 - \frac{\sum_{N95} |(S_1 + S_3) - (S_2 + S_4)|}{1/2 \sum_{N95} |S_1 + S_2 + S_3 + S_4|} \quad (5)$$

where  $S_i$  ( $i = 1, 2, 3, 4$ ) is the measurement obtained from each of the four gauges of the borehole strainmeter.  $N$  is

**Fig. 2** Analytical solution of SG equation, **a** displacement, **b** strain



the total number of the incremental time series data points. The subscript 95 indicates that 5% of the data, termed “bad points,” are removed. Generally,  $0 < C_{95} < 1$ . For credible data, the index should be close to unity. The larger the value of the index, the higher the credibility. Figure 3 shows that curves of  $S_1 + S_3$  and  $S_2 + S_4$  of Guza observation are almost the same. Because the “bad points” are hard to confirm, we only remove some “bad points” according to daily log, such as rainfall or device maintenance. Then we calculate  $C_{95} = 0.9563$ . From Fig. 3 we could also see there is an overall amplitude drift between curves of  $S_1 + S_3$  and  $S_2 + S_4$ . If we remove the drift, the  $C_{95}$  will be higher. That this is true for the abnormal pulses indicates the strain nature of the anomalous changes. A self-check function of the strainmeter also confirmed the credibility of the observation (Qiu et al. 2011).

Figure 4 illustrates the N–S component of the original curves of the borehole strain changes at the Guza station from February 15–28, 2008 (Fig. 4a) and the highlighted section on February 28, 2008 (Fig. 4b), where significant pulse-like shapes can be observed. Few earthquake events had been located in the adjacent area of Guza with sparse seismometer network. Only one event above Ms4 was recorded on February 27, 2008. Based on the detailed and reliable analysis of the anomalies, Qiu et al. (2011) suggested that the recurring anomalous changes were not caused by environmental disturbances and were significantly different from the seasonal variations. The anomalous changes were found to be consistent with

changes in the long-term trend and the coseismic step-like changes, which indicated that they were probably the result of tectonic movements. By comparing Figs. 2 and 4, it is also apparent that the bell-shaped solution obtained from Eq. (4) is similar to the pulse-like shapes observed in the actual data. Can these pulses be generated by the slick-slip motion described by the SG equation?

### Numerical simulation method

This section models the propagation of 1-D nonlinear wave using finite-difference method, while numerical stability was obtained by flux-corrected transport (FCT) method (Zhou and Wang 2015). Equation (4) is employed here as the model for earthquake source.

The 1-D nonlinear wave equation can be written as:

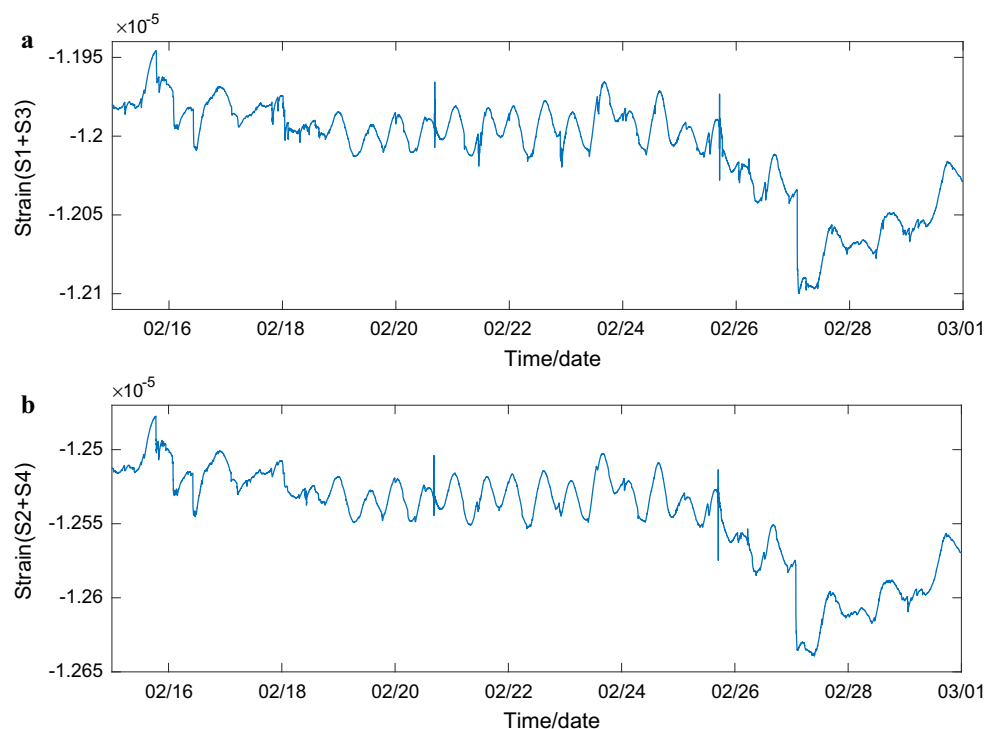
$$\frac{1}{v^2} \frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial z^2} = \beta_1 \frac{\partial}{\partial z} \left( \frac{\partial u}{\partial z} \right)^2 + \beta_2 \frac{\partial}{\partial z} \left( \frac{\partial u}{\partial z} \right)^3 + \alpha \left( \frac{\partial^4 u}{\partial z^4} \right) \quad (6)$$

where  $v$  indicates the P-wave velocity at the linear background medium,  $u$  is the displacement,  $t$  is the time,  $z$  is the location of the horizontal axis,  $\beta_1$  and  $\beta_2$  are the introduced nonlinear coefficients, and  $\alpha$  is the coefficient of dispersion.

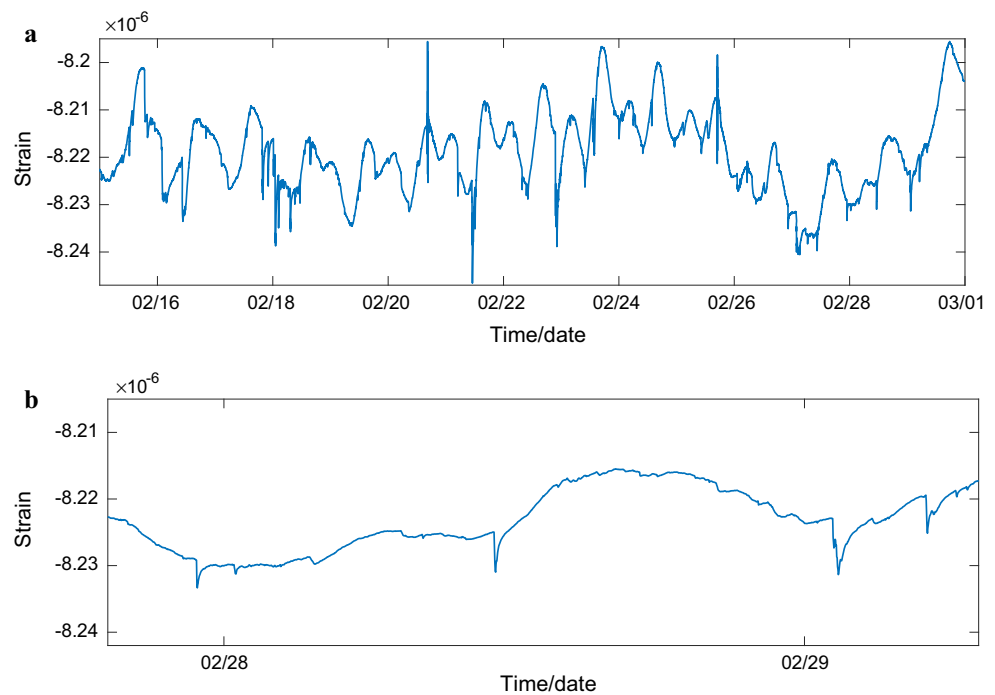
As Eq. (6) contains high-order derivatives, it is transformed as follows:

$$\varepsilon = \partial_z u$$

**Fig. 3** Strain recording at the Guza station for the period of February 15–28, 2008, **a**  $S_1 + S_3$  component, **b**  $S_2 + S_4$  component



**Fig. 4** Data of minute strain recording at the Guza station, **a** period of February 15–28, **b** February 28



$$\sigma = M[\varepsilon + \beta_1 \varepsilon^2 + \beta_2 \varepsilon^3 + \alpha \partial_z^2 \varepsilon] \quad (7)$$

$$\rho \partial_t^2 u = \partial_z \sigma + f_z$$

where  $\sigma$  represents the stress,  $\varepsilon$  is the strain,  $M$  is the bulk modulus, and  $\rho$  is the density. Other parameters are the same as in Eq. (6).

The spatial sampling is taken as  $\Delta x = 2000$  m, temporal sampling  $\Delta t = 0.1$  s, density  $\rho = 2000.0$  kg/m<sup>3</sup>, spatial grid size is 6000 (with the earthquake source placed at the center of the space), and elastic wave velocity  $v = 4000$  m/s. According to Abeele (1996), the first and second nonlinear parameters ( $\beta_1$  and  $\beta_2$ ) have been found to range anywhere between 10 and  $10^4$  for  $\beta_1$  and between  $10^3$  and  $10^9$  for  $\beta_2$ . For some combinations of nonlinear and dispersive parameters, we have discussed in another paper (Zhou and Wang 2015), now we focus on the influence of  $\beta_2$  on the propagation of pulse. In Eq. (4), we set  $V_\alpha = 10$  m/s (Bykov 2008) and  $a \approx 3$  cm (Gershenzon et al. 2011). And  $\Delta$  is roughly estimated as a constant 200 according to the period of actual pulse. In the following modeling, we choose  $\beta_1 = \alpha = 0$  and  $\beta_2 = 1.0 \times 10^6$ .

Figure 5 shows the simulation results. It can be observed that the waveform tilted toward the propagation direction, indicating effects of the nonlinear terms during propagation. When the propagation arrived at a certain distance, the wavefront exhibited an upright shape. Moreover, because the attenuation term and spherical diffusion were not considered in this model, the amplitude did not experience significant attenuation. The value of the nonlinear

parameter  $\beta_2$  is found to have direct effect on the waveform distortion (forward tilting of the waveform); in other words, the wavefront of the pulse will reach the upright shape earlier with a larger  $\beta_2$  (Fig. 6).

However, a larger  $\beta_2$  also leads to a more unstable numerical simulation result, as it is difficult to suppress the waveform oscillation caused by the numerical dispersion even with the FCT method. By comparing the numerical simulation results and the actual data obtained from the Guza station (Fig. 4), the simulation results were found to be very similar to the pulse-like strain changes that were observed at the Guza station. In order to further analyze and compare the results, a pulse-like strain anomaly at Guza on February 28, 2008 (Fig. 7a), was chosen for further study. However, because the anomalous changes in the actual data were superimposed on the pre-existing solid tidal deformation, while the wave equations in the numerical simulation had not considered any permanent deformation, only part of the strain anomaly with pulse was extracted to reduce the effect of solid tidal deformation on the waveform. By modifying the parameters in the numerical simulation ( $\beta_2 = 3.0 \times 10^6$ ,  $V_\alpha = 1$  m/s, while keeping others unchanged), a fitting was conducted between the simulation result and the pulse-like anomaly. Two curves fit well as demonstrated in Fig. 7b.

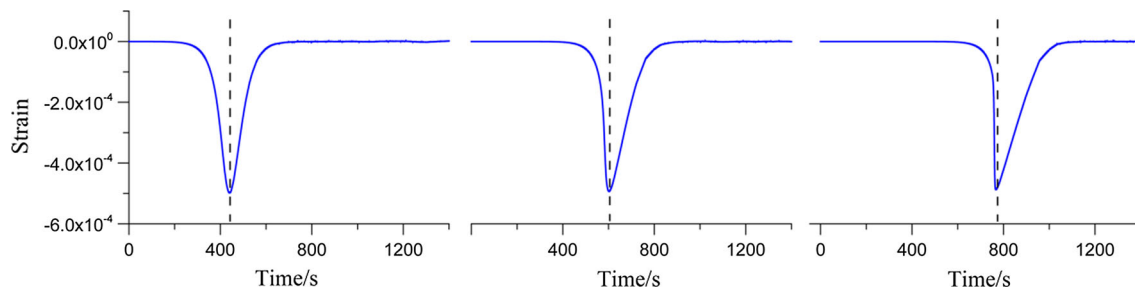


Fig. 5 Nonlinear evolution of the pulse

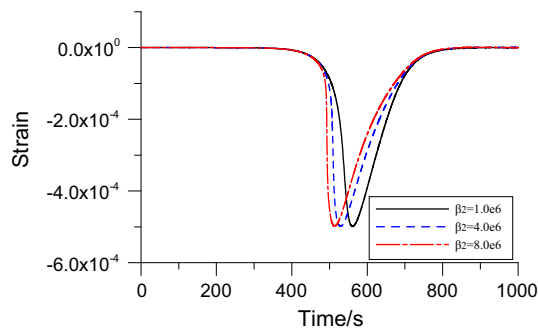


Fig. 6 Effects of different  $\beta_2$  on pulse

## Discussion

According to the aforementioned Bykov's unsteady-state slip model and the results of the numerical simulation, one possible interpretation is proposed in the following: During the seismogenic process of the Wenchuan earthquake, a series of stick-slip tectonic movements similar to the unsteady-state slip model occurred in succession at the seismogenic zone and generated the originally symmetrical strain pulse signals. Because of the nonlinear effect of the medium of the Earth, the pulses experienced a forward

tilting distortion during propagation, as illustrated in Fig. 5, and the corresponding pulses were received by the borehole strainmeter. However, several questions about this interpretation need to be discussed: (1) why can the pulse strain changes only be observed at the Guza station but not at most other stations? (2) What is the form of propagation for the pulses? (3) Can  $V_\alpha$  be as low as few meters per second? (4) Are these kinds of pulses only generated at the early stage of the seismogenic period, and can the presence of them serve as a clear forewarning signal for earthquakes?

To answer the first question, Qiu et al. (2011) pointed out that the pulse-like strain was only observed at the Guza station because it was closest to the epicenter, while other stations were at least 300 km away. As strain changes attenuate with increasing distance, it is understandable that the signal was not observed at other monitoring stations. Figure 8 illustrates the geographical distribution of the borehole strainmeter stations surrounding the Wenchuan earthquake. The Guza station is found to be the only station within close proximity to the epicenter. The strong magnitude of the Wenchuan earthquake led to a surface rupture zone that was 240–275 km long on the Beichuan Fault and 70–80 km long on the

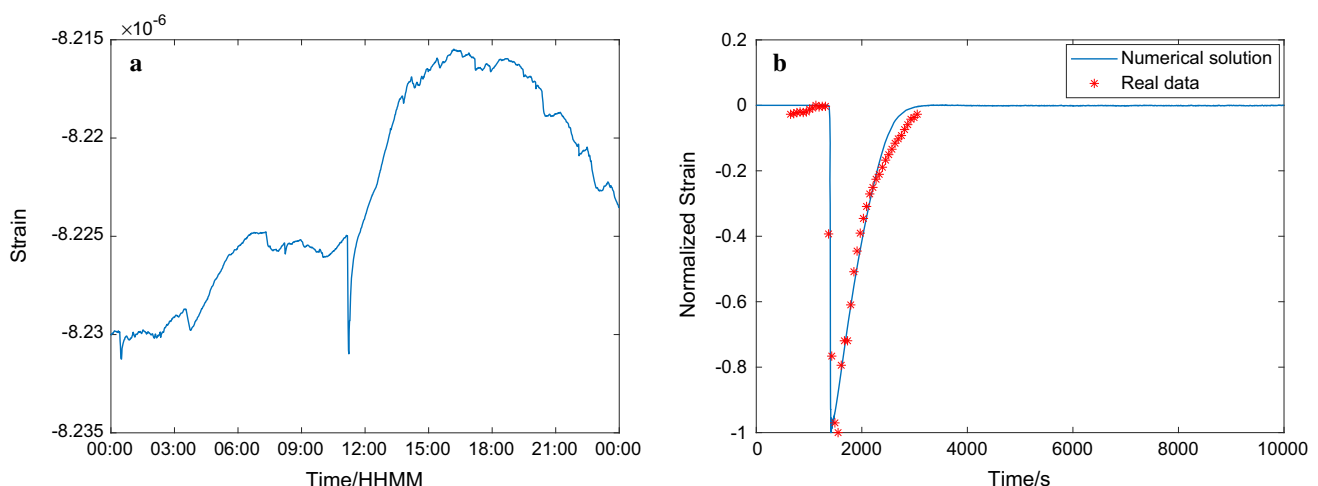
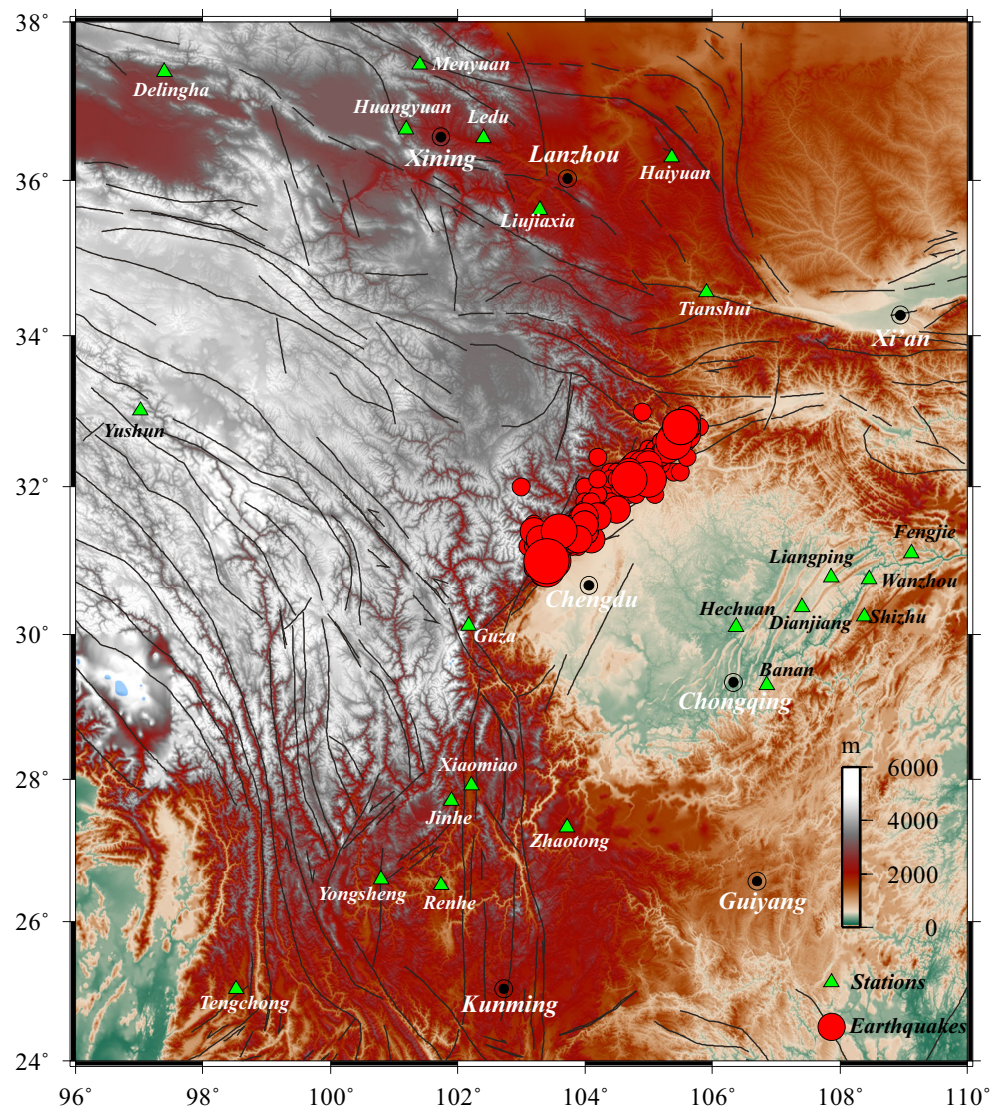


Fig. 7 Comparison of numerical simulation with real pulse, **a** original data, **b** comparison result



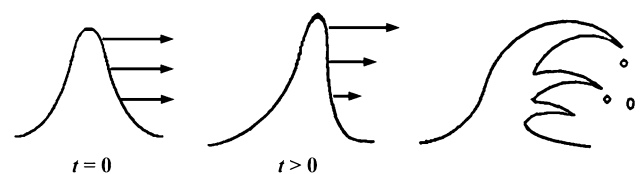
**Fig. 8** Spatial distribution of borehole strain stations

Pengguan Fault (Wang et al. 2011). Figure 8 also contains information about the areas affected by aftershocks. Taking the length of the whole rupture zone into consideration, the seismic station at Tianshui should have been able to receive similar anomalous signals. However, this station only started to record data from 2014.

In addition, the absence of strain anomaly signals received by other stations which are far from the source may be due to the convergence effect of pulse propagation (amplitude decreasing by geometric diffusion is also a reason). According to the numerical simulation results, the waveform of the pulses experience distortion (wavefront will forward tilt) during propagation. When the propagation reaches a certain distance, the wavefront would exhibit an upright shape. If the propagation continues, the forward tilting of the wavefront of the pulses is likely to continue, maybe resulting in a wavefront collapse at some time due

to an excessive increase in the tilt angle (Fig. 9). The loss of stability of the pulses led to its disappearance after a certain propagation distance. Hence, this kind of pulses cannot propagate for long distance.

For the propagation of pulses, two kinds of nonlinear effects could lead to these special pulses. One is what we discussed above that it is the nonlinear effects in the wave propagation process. The other is when considering both friction and stress [in Eq. (1)] in the process of unsteady-

**Fig. 9** Schematic diagram of pulse collapse

state slip, the source would have some distortions. In the latter case, numerical method is needed to solve the equation (1). We will discuss it specifically in the further study. For  $V_s$ , Bykov (2014, 2016) proposed that the propagation velocity of the strain solitary wave could be as low as a few kilometers per day or an average velocity of 1000 km/a. Gershenzon et al. (2009) suggested that when the velocity of the elastic wave is 6000 m/s, the strain solitary wave velocity can be set to 10–100 km/a. Erickson et al. (2011) set the propagation velocity of solitary wave to 1 m/s based on the dynamic fracture of the BK model during their numerical simulation. Many other publications have also described the propagation mode of solitary wave. For instance, Sharon and Fineberg (Sharon et al. 2001; Fineberg et al. 2001) both suggested that solitary waves propagate along the rapid rupturing fissure tip. Erickson et al. (2011) found that the solitary wave solution in the numerical simulation of dynamic fractures can be comprehended as a mode of propagation at the rupture along the fault plane. Combining the above hypotheses with the simulation results of this study, the propagation mode of this kind of pulses may be similar to a boat moving in the water: the pulse propagates with a velocity lower than the elastic wave along the fault plane like a boat moves toward one direction with a certain velocity which is lower than water wave. As the pulse is propagating along the fault plane, it may also act as a source and propagate to its surroundings in the form of elastic wave, which is similar to the generation and propagation of water waves when a boat is moving.

This kind of pulses could not be only generated prior to earthquakes. Sometimes during the post-earthquake adjustment process, stick–slip movements may also occur and lead to this nonlinear phenomenon. For example, the anomalous borehole strain changes that were observed at the Guza station prior to the Wenchuan earthquake did not disappear right after the earthquake ended. Instead, they were observed to be diminishing gradually until March 2009, at which point their complete disappearance was recorded. It is clear that stick–slip with an amplitude comparable with natural earthquakes occurs under a certain range of conditions (Brace and Byerlee 1966). Stick–slips may be recorded as “foreshocks” leading to “main shocks” and followed by “aftershocks” each releasing different levels of acoustic energy (Khazaei et al. 2016). So, the study on these pulses or solitary wave can not only help us understand the generation mechanism of the pre-earthquake strain anomalies, but also indicate the active areas with stick–slip movements, which might be prone to earthquakes.

## Conclusions

In this paper, we derived stable solutions of displacement and strain dimension based on Bykov’s unsteady-state slip model. Then, the nonlinear propagation effect of the pulses was modeled using finite-difference modeling, and the factors affecting their propagation and evolution were also studied. Finally, through a comparison between the modeling results and the actual strainmeter data, one possible potential physical mechanism for the generation of strain pulses was discussed.

- (1) Simulation of the nonlinear propagation of pulse was performed using the FCT finite-difference method in this study. When the appropriate nonlinear parameters were chosen (i.e.,  $\beta_2 \neq 0$ ,  $\beta_1 = \alpha=0$ ), the pulse wavefront would experience forward tilting during its propagation. When the propagation reached a certain distance, the wavefront was found to exhibit an upright shape. The value of the nonlinear parameter  $\beta_2$  was also found which had direct influence on the waveform distortion (forward tilting of the wavefront). That is, the wavefront will reach the upright shape earlier with a larger  $\beta_2$ .
- (2) By comparing between nonlinear wave modeling result and the actual data from the borehole strainmeter at the Guza station, one possible interpretation was proposed: earthquake faults occurred as stick–slip tectonic movements in the seismogenic zone, which are similar to the unsteady-state slip model. Because of nonlinear effects in the wave propagation process, the pulses experienced a forward tilting distortion and were finally received by the borehole strainmeter. Friction and stress in the process of unsteady-state slip may also lead to the waveform distortion.
- (3) The convergence effect of pulse may be one reason for its inability to propagate for a long distance. The numerical simulation results showed that the pulse waveform experienced forward tilt during propagation. When it reached a certain distance, the wavefront would exhibit an upright form, and the deformation was likely to continue, resulting in a wavefront collapse at a certain point due to an excessive increase in the tilt angle. The stability of the pulse was destroyed and then disappeared.
- (4) When the pulse was propagating along the fault plane, it might also act as a source and spread to its surroundings in the form of elastic wave, which is similar to the generation and propagation of water waves when a boat is moving.



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**Author contributions** CZ conceived the approach to the research, performed the nonlinear wave modeling and analysis, and wrote the paper. QW contributed to the analysis and interpretation of the phenomenon. LZ contributed to plotting some figures and manuscript writing. CW helped to process strain pulses data.

## Compliance with ethical standards

**Conflict of interest** The Authors declare that they have no conflict of interests.

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